ACCELERATOR GROUP
European Physical Society

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Hosting institutions

Elettra Sincrotrone Trieste

INFN
Istituto Nazionale di Fisica Nucleare

Student Tutorials 5,6 May

M. Comunian

IPAC23

Michele Comunian (INFN – LNL)

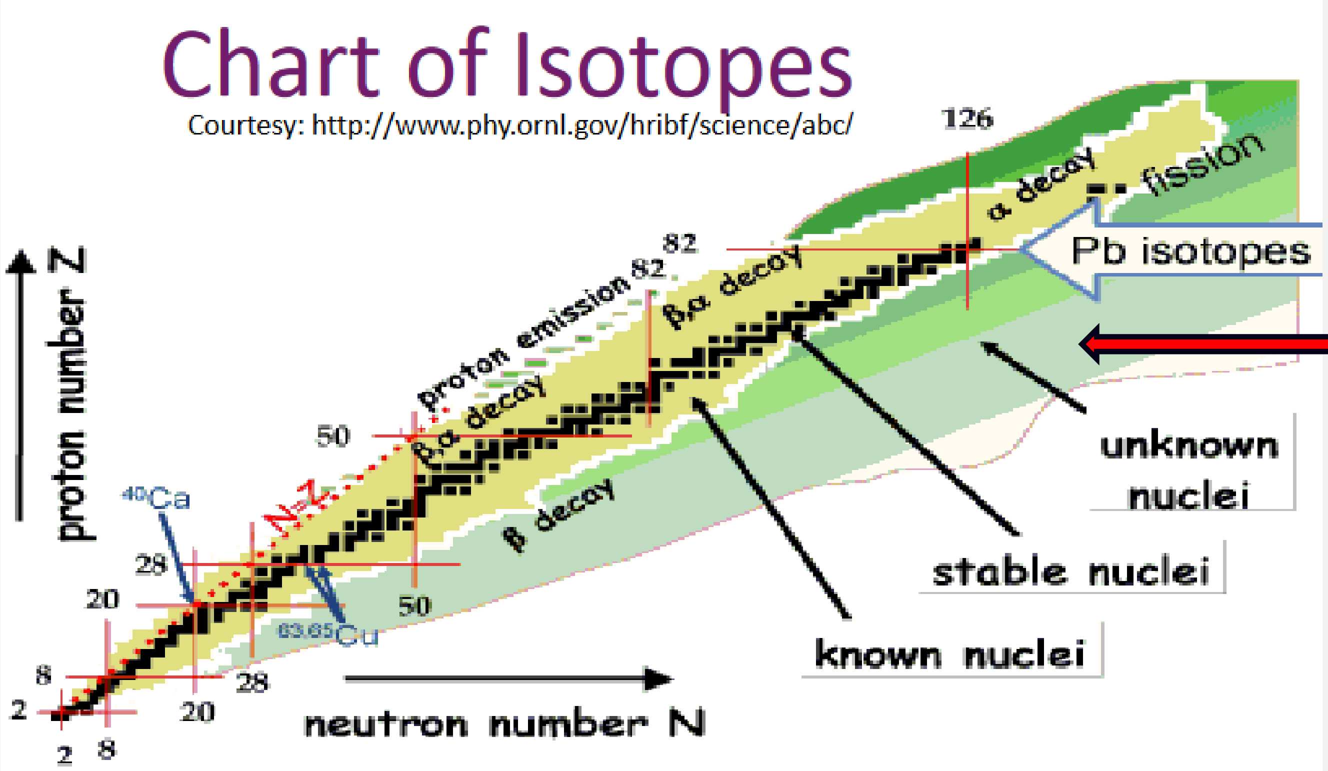
Facilities for Radioactive Ion Beams

Facilities for Radioactive/Rare Ion Beams

- What is a RiBs Facilities
- Overview of main RiBs Facilities
- Some specific topics:
- Beam generation (driver, target)
- Beam selection (hrs, cooler)
- Beam acceleration (charge breeder, post)
- SPES as example of RiBs facility

What is a RiBs facilities

Radioactive Ion Beams are beams of atomic nuclei that are radioactive, meaning that they spontaneously decay and emit radiation. These beams are generated by accelerating artificially created isotopes to high energies using particle accelerators.
The resulting beam of radioactive ions can be used for a variety of scientific applications,
including nuclear physics research, astrophysics studies, and medical applications such as cancer treatment.
The unique properties of these beams allow scientists to study and control the behavior of individual atomic nuclei,
providing insights into the fundamental nature of matter and energy.



Courtesy: http://www.phy.ornl.gov/hribf/science/abc/

You are here!

Practical use of RiBs:

Radioactive isotopes have a variety of practical uses, including:

1. **Dating fossils and rocks**: Scientists use radioactive isotopes to determine the age of rocks and fossils by measuring the rate of decay of isotopes such as Carbon-14 and Uranium.
2. **Medical imaging**: Radioactive isotopes such as Technetium-99m are used to create images of the body during medical procedures such as bone scans and PET scans.
3. **Cancer treatment**: Radiation therapy uses high-energy ionizing radiation, often delivered through radioactive isotopes such as Iodine-131 and Cobalt-60, to kill cancer cells and shrink tumors.
4. **Industrial applications**: Radioactive isotopes are used in a variety of industrial applications such as oil exploration, quality control in manufacturing, and detecting leaks in pipes and containers.
5. **Energy production**: Nuclear power plants use radioactive isotopes such as Uranium-235 and Plutonium-239 to generate electricity through nuclear reactions.
6. **Agriculture**: Radioactive isotopes are used to study soil erosion and plant nutrient uptake, as well as to control insect and pest populations in agriculture.

All these practical use need a better “know how” (Theory) on the RiBs ions

- Cross sections of ions (problems with extremely low production cross sections, force between nucleons)
- Decay time (problems with very short lifetime, hadrons properties)
- Decay modes (problems of unwanted species in the same nuclear reaction, complexity of nucleons interactions)
- New ions identification (problems of high energy beams, stability limits?)

Chart of isotopes evolution

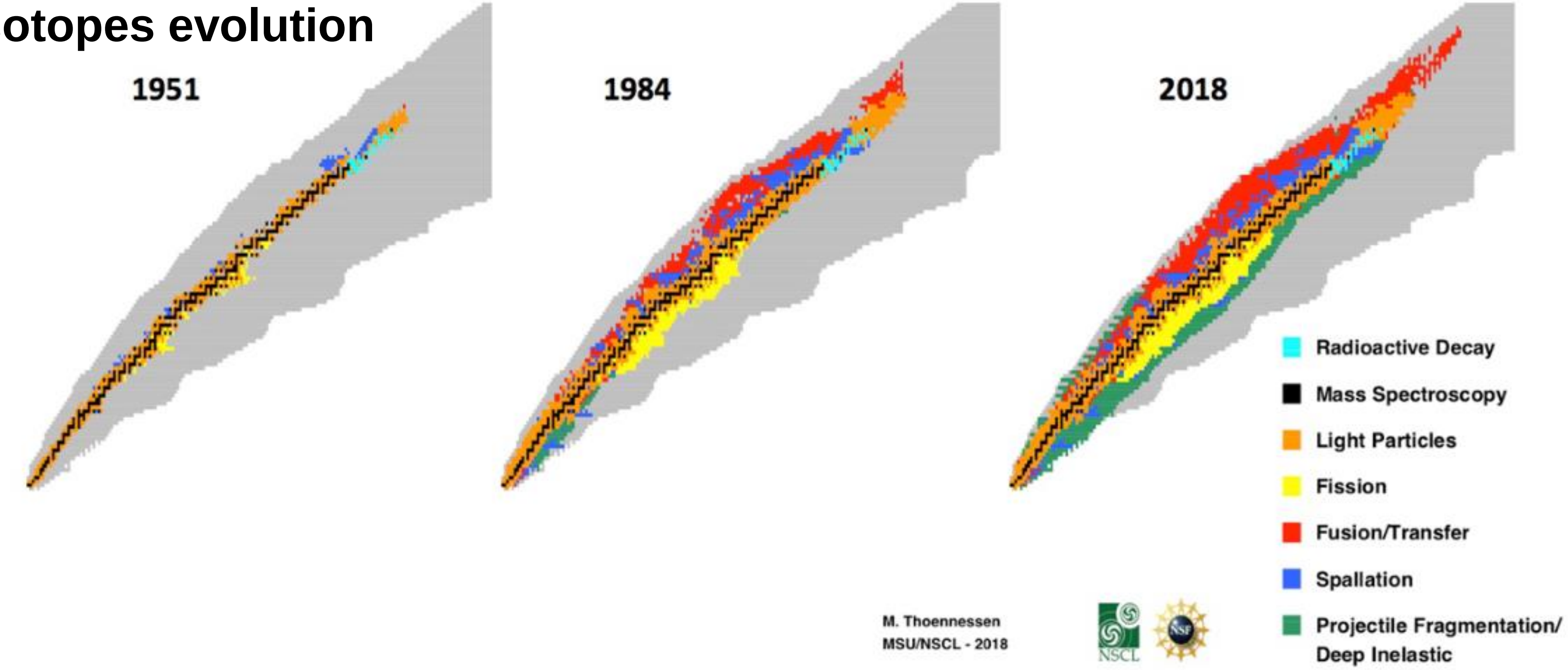
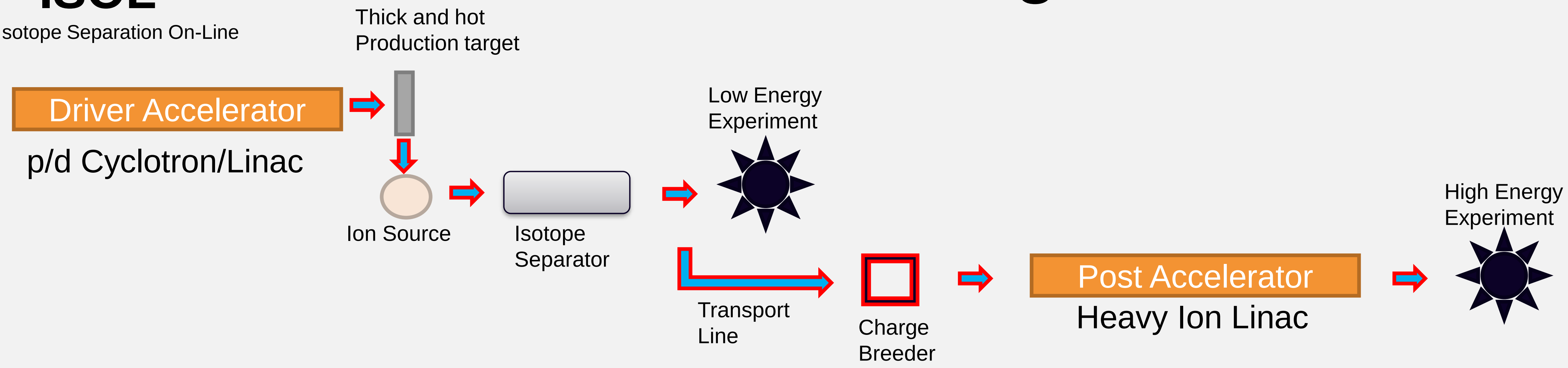


Figure 3 The two-dimension plots with protons on y-axis and neutron on x-axis, courtesy of M. Thoennessen, show in grey the expected nuclei. On the left plot, the nuclei known prior to the use of the ISOL-method where reaction with light particles and some spontaneous fission allow for the production of the 900 nuclei known. The central plot shows the 2257 nuclei known prior to the use of in-flight method. Neutron deficient nuclei were produced by fusion-evaporation, fission, fragmentation and spallation in thick targets. The nuclei chart on the right shows the situation in December of 2018 with 3302 nuclear species identified [M. Thoennessen, International Journal of Modern Physics E 28 (2019) 1930002]. The advancement into the so-called "Terra Incognita" thanks to the in-flight facilities is outstanding.

How to generate RiBs

ISOL

Isotope Separation On-Line



Thick and hot
Production target

Driver Accelerator
p/d Cyclotron/Linac

Ion Source

Isotope
Separator

Low Energy
Experiment

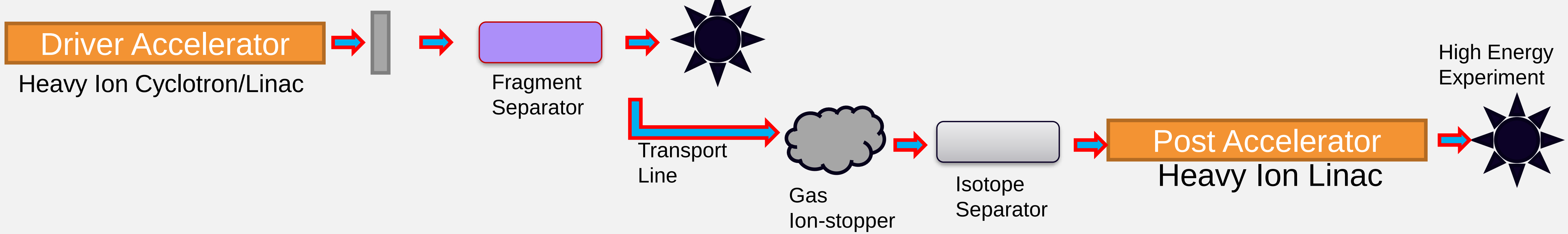
Transport
Line

Charge
Breeder

Post Accelerator
Heavy Ion Linac

High Energy
Experiment

In-Flight



Thin
Production
target

Driver Accelerator
Heavy Ion Cyclotron/Linac

Fragment
Separator

High Energy
Experiment

Transport
Line

Gas
Ion-stopper

Isotope
Separator

Post Accelerator
Heavy Ion Linac

High Energy
Experiment

ISOL METHOD

Pro:

- Small Beam emittance
- Small energy Spread
- High quality pure beams (Spectrometer/Laser source)
- Parasitic use of main facility beam time

Cons:

- Low Energy beam
- Need post accelerator
- Slow production method (decay losses)
- Chemistry needed

In-Flight METHOD

Pro:

- High Energy
- Fast production method (no decay losses)
- No Chemistry

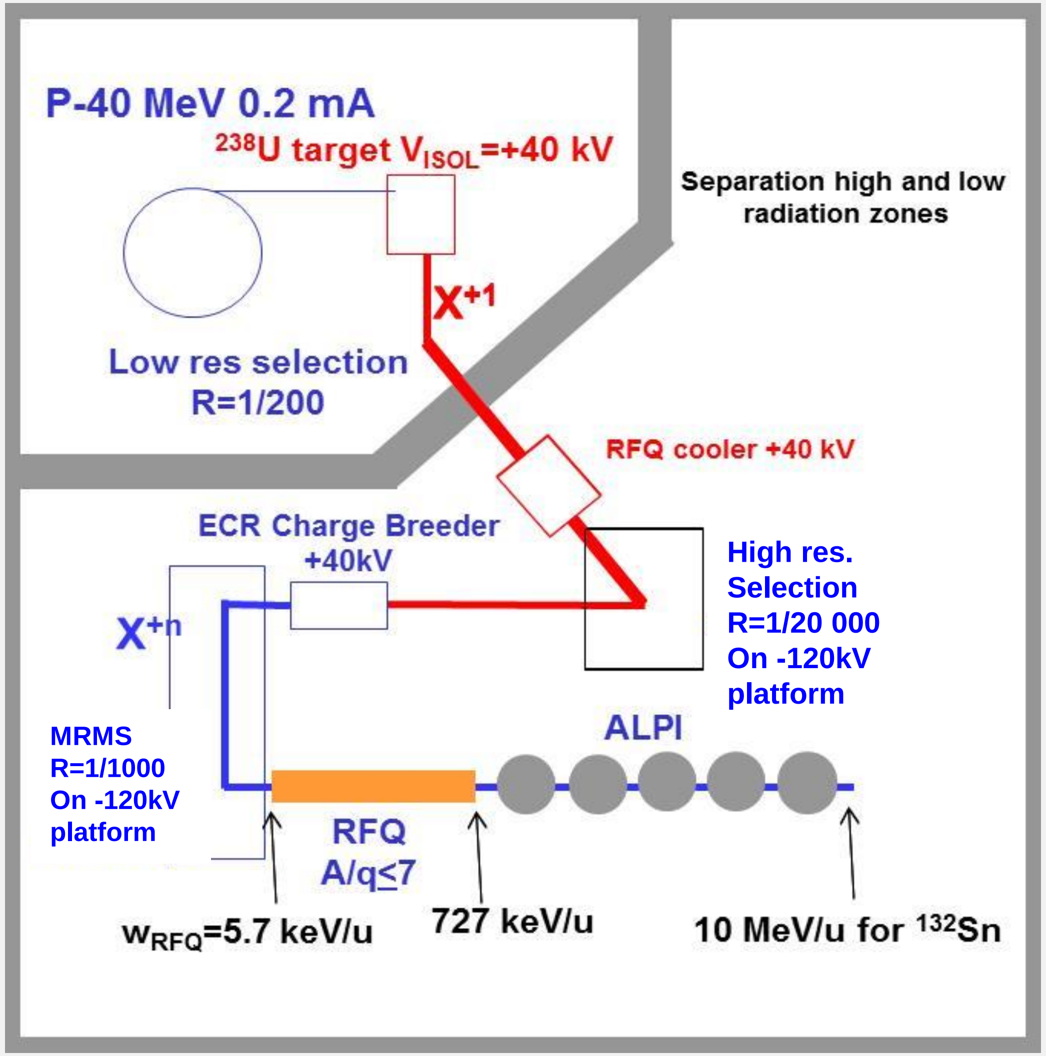
Cons:

- Cocktail of beams
- Difficult to decrease energy
- Uneasy to purify the beam
- High emittance/energy spread
- Need a specific facility

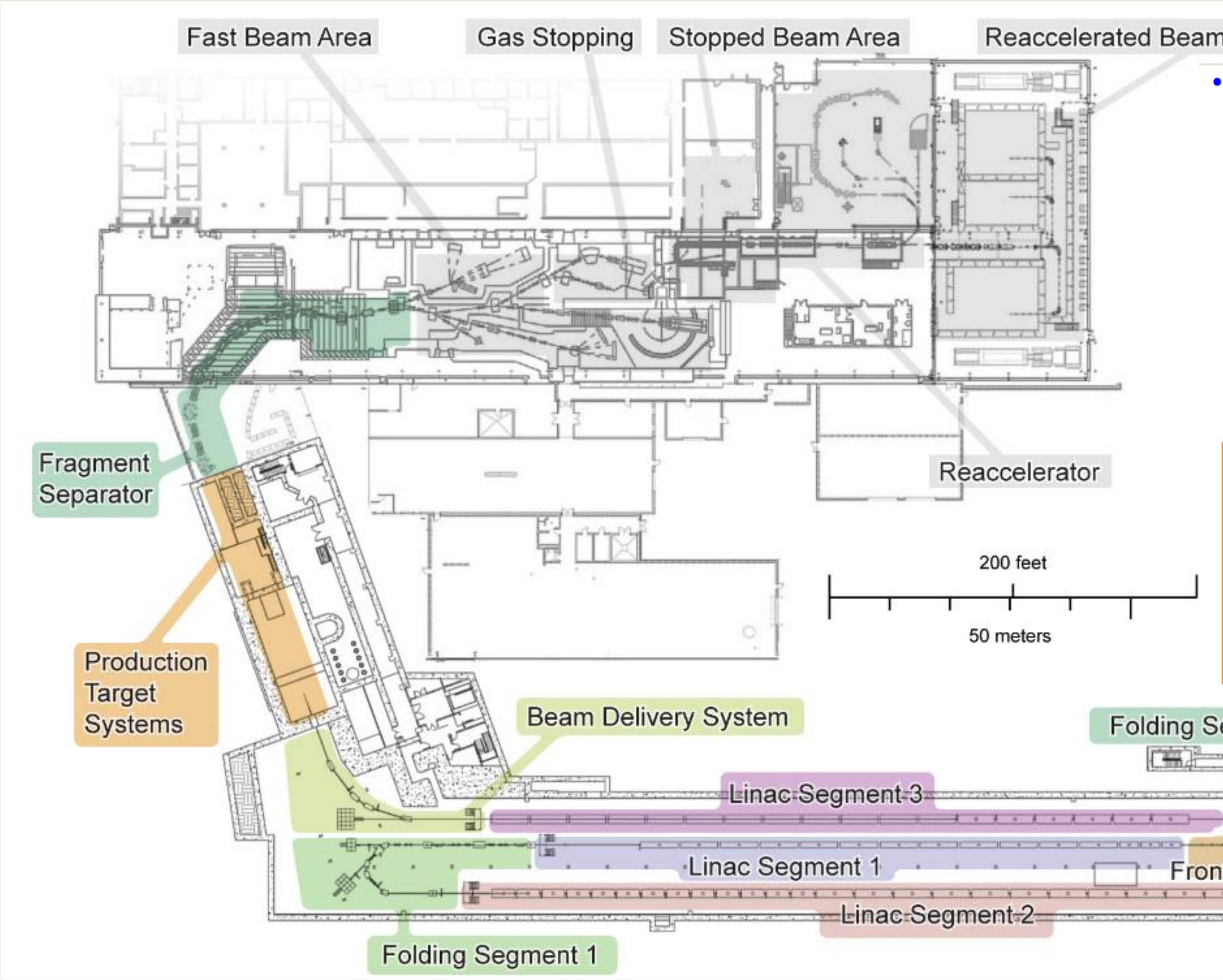
Example of ISOL facility (SPES)

- The beam preparation scheme satisfies various requirements:

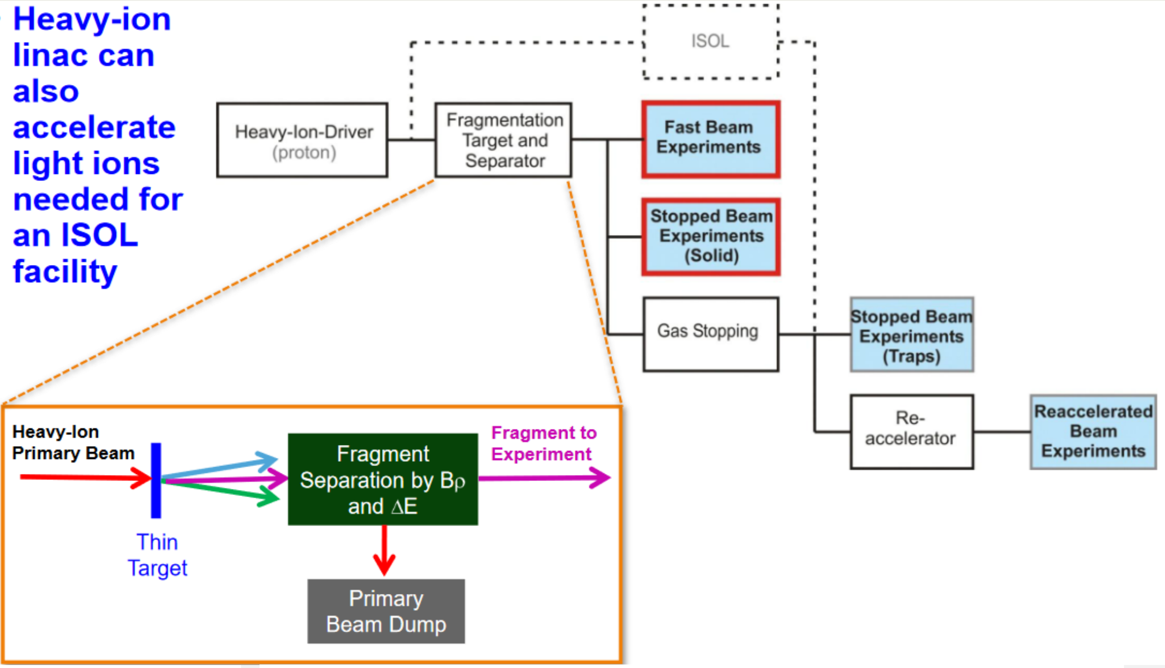
1. the zone with worst radiation protection issues is reduced by means of the first isobar selection (resolution R=1/200).
2. after that with an RFQ cooler the beam energy spread and transverse emittance are reduced both for further separation and to cope with the charge breeder acceptance (about 1 eV).
3. HRMS and MRMS (high and medium resolution mass spectrometers, R=1/20000 and R=1/1000 respectively) are used to select the RNB (with good transmission) and to suppress the contaminants from the charge breeder source.
4. Both the HRMS and the MRMS are installed on a negative voltage platform, to decrease the beam geometrical emittance, the relative energy spread and to keep the dipole field in a manageable range (>0.1 T).
5. The 7 m long RFQ has an internal bunching and relatively high output energy; this easies the setting and allows 90% transmission into ALPI longitudinal acceptance (constraint deriving from quite long ALPI period, 4 m).
6. An external 5 MHz buncher before the RFQ will be available for specific experiments (at the price of about 50% beam transmission).
7. The dispersion function is carefully managed in the various transport lines; where possible the transport is achromatic, otherwise the dispersion is kept low (in particular at RFQ input D=0, D' is about 50 rad).



Example of In-Flight facility (FRIB)



- **Heavy-ion linac can also accelerate light ions needed for an ISOL facility**



- Our experience shows that the linac model (online and offline) predicts the beam dynamics very well except for transverse beam steering due to misalignments

First generation RiBs Facilities

2E9 pps=0.3 pA

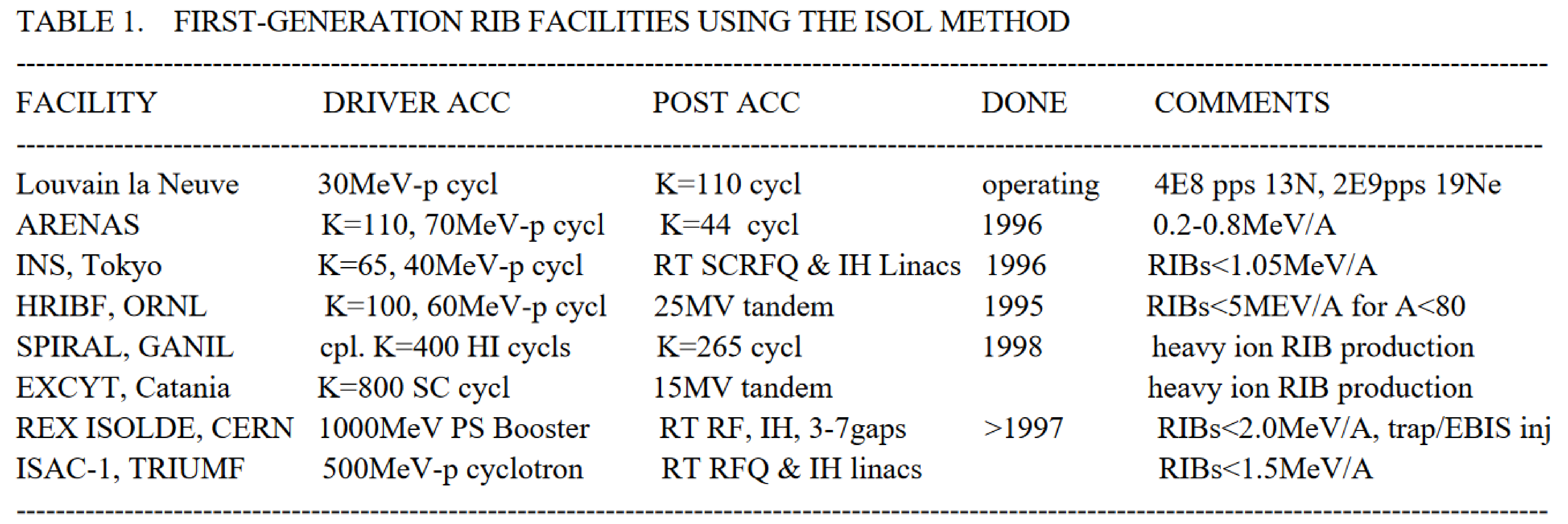
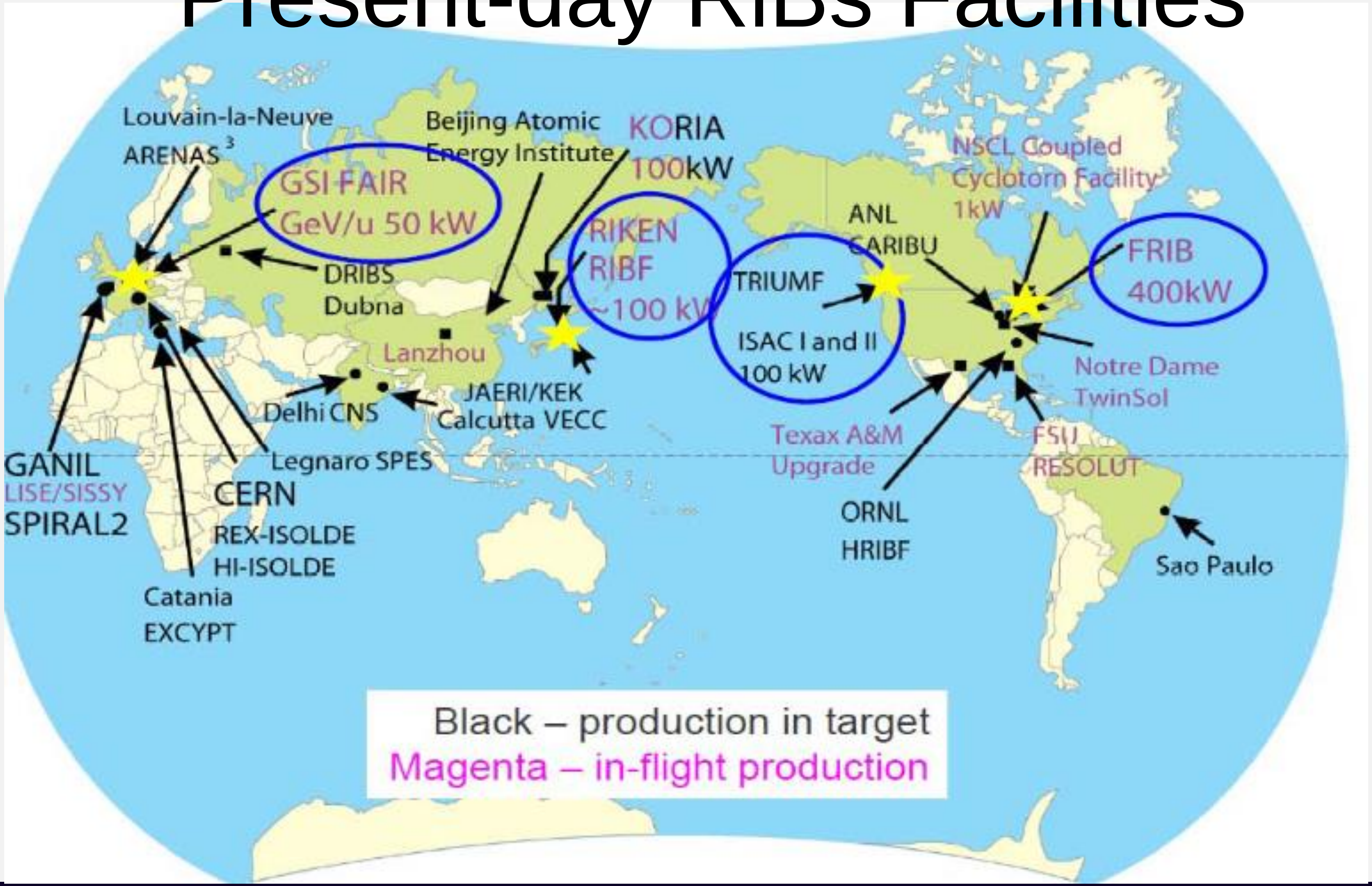


TABLE 1. FIRST-GENERATION RIB FACILITIES USING THE ISOL METHOD

FACILITY	DRIVER ACC	POST ACC	DONE	COMMENTS
Louvain la Neuve	30MeV-p cycl	K=110 cycl	operating	4E8 pps 13N, 2E9pps 19Ne
ARENAS	K=110, 70MeV-p cycl	K=44 cycl	1996	0.2-0.8MeV/A
INS, Tokyo	K=65, 40MeV-p cycl	RT SCRFQ & IH Linacs	1996	RIBs<1.05MeV/A
HRIBF, ORNL	K=100, 60MeV-p cycl	25MV tandem	1995	RIBs<5MEV/A for A<80
SPIRAL, GANIL	cpl. K=400 HI cycls	K=265 cycl	1998	heavy ion RIB production
EXCYT, Catania	K=800 SC cycl	15MV tandem		heavy ion RIB production
REX ISOLDE, CERN	1000MeV PS Booster	RT RF, IH, 3-7gaps	>1997	RIBs<2.0MeV/A, trap/EBIS inj
ISAC-1, TRIUMF	500MeV-p cyclotron	RT RFQ & IH linacs		RIBs<1.5MeV/A

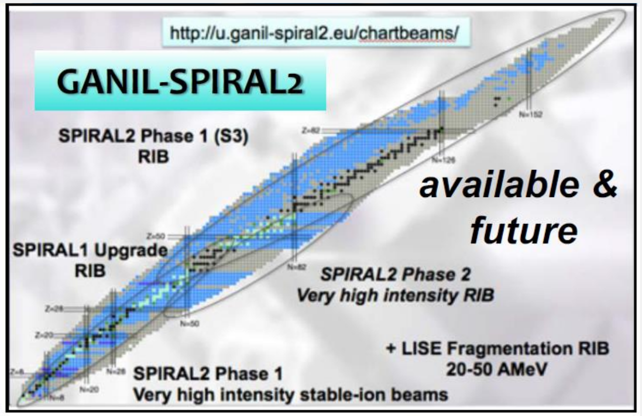
However, they are all limited in some way with respect to what is technically feasible, either in RIB species, RIB intensity, or RIB energy.

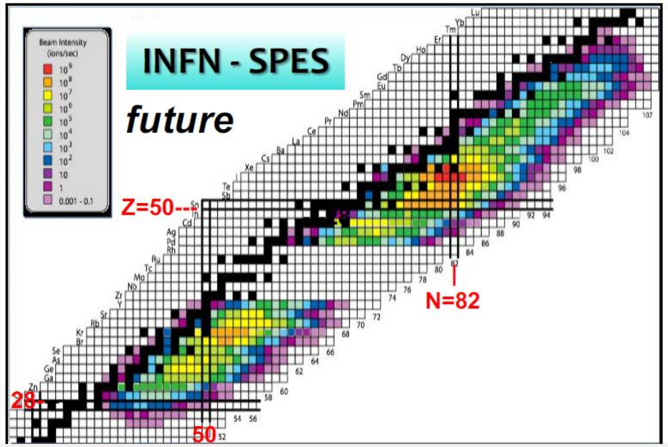
Present-day RiBs Facilities

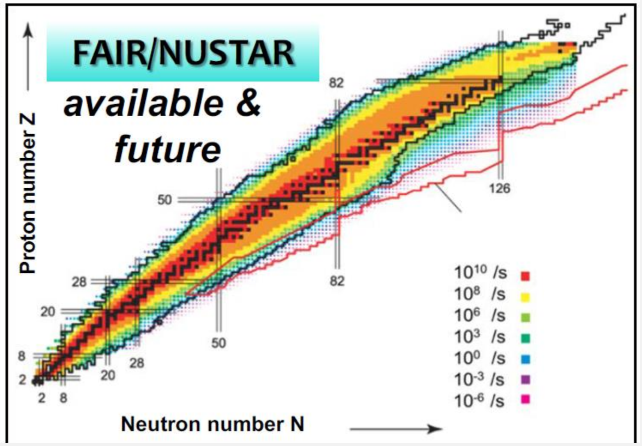


Black – production in target
Magenta – in-flight production

RiBs Facilities (European)



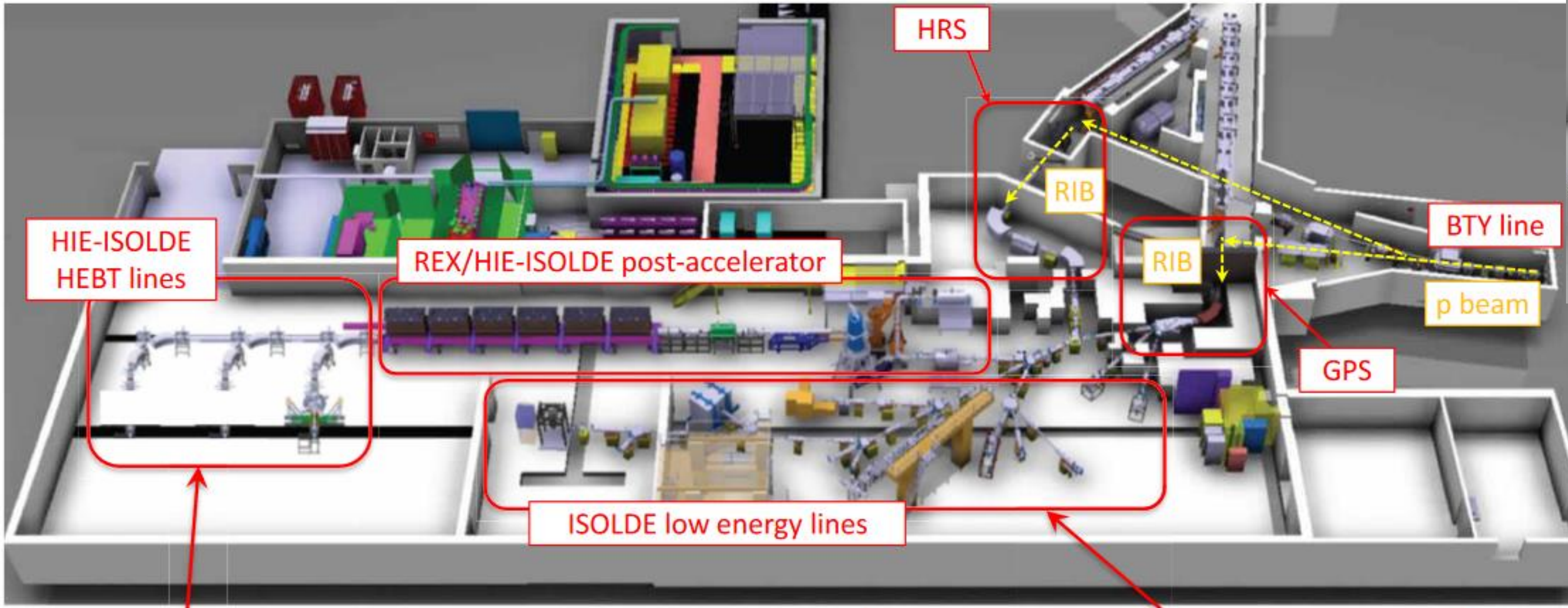




HIE ISOLDE

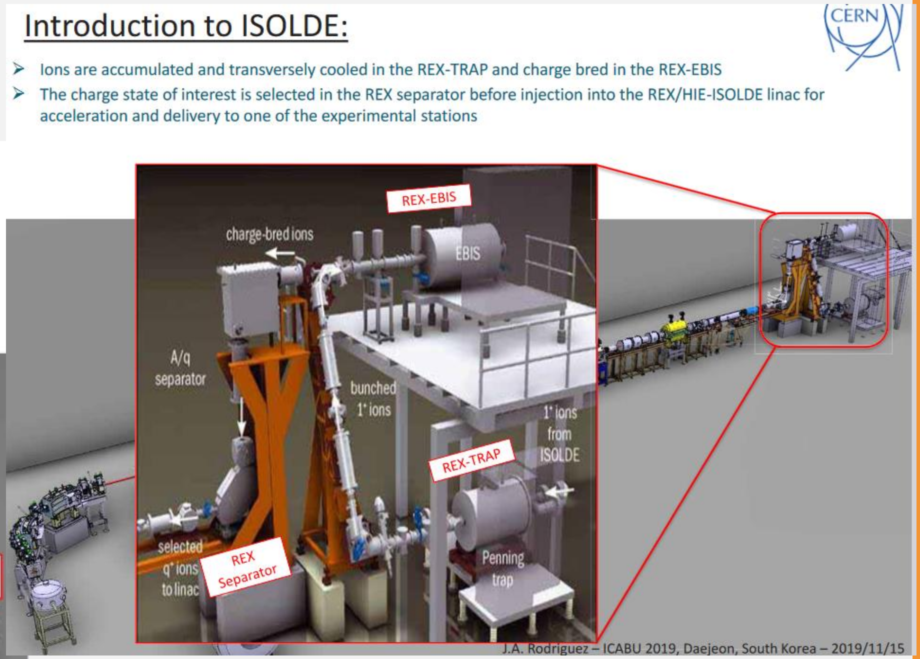
- Beam delivery to low energy beamlines
- Or post-acceleration with REX + HIE-ISOLDE and delivery to HIE-ISOLDE beamlines

Nuclear physics
Astrophysics
Fundamental interactions
Material science



High energy experimental stations:
- Miniball
- ISS
- Scattering Chamber

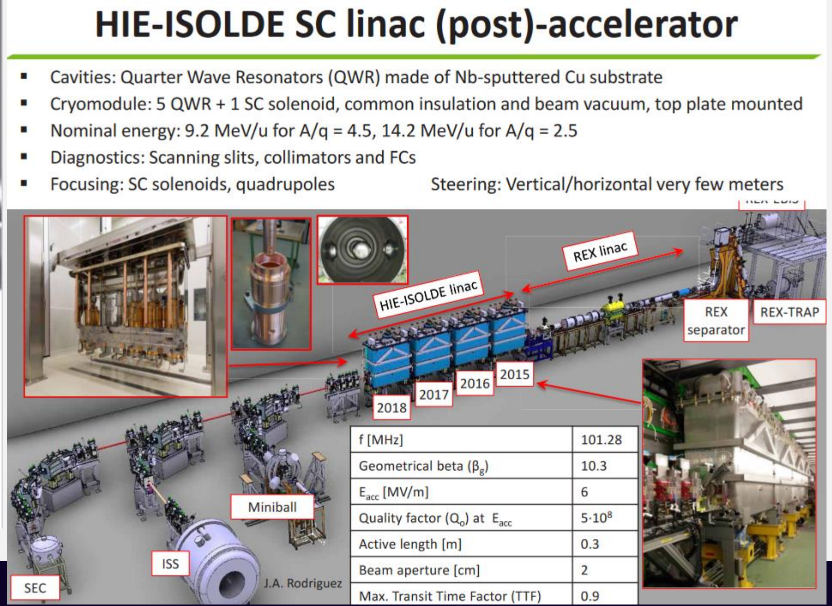
Low energy experimental stations:
- IDS
- ISOLTRAP
- CRIS
- COLLAPS
- SSP stations
- VITO
- NICOLE
- WISARD



Introduction to ISOLDE:

- Ions are accumulated and transversely cooled in the REX-TRAP and charge bred in the REX-EBIS
- The charge state of interest is selected in the REX separator before injection into the REX/HIE-ISOLDE linac for acceleration and delivery to one of the experimental stations

J.A. Rodriguez – ICABU 2019, Daejeon, South Korea – 2019/11/15



HIE-ISOLDE SC linac (post)-accelerator

- Cavities: Quarter Wave Resonators (QWR) made of Nb-sputtered Cu substrate
- Cryomodule: 5 QWR + 1 SC solenoid, common insulation and beam vacuum, top plate mounted
- Nominal energy: 9.2 MeV/u for A/q = 4.5, 14.2 MeV/u for A/q = 2.5
- Diagnostics: Scanning slits, collimators and FCs
- Focusing: SC solenoids, quadrupoles Steering: Vertical/horizontal very few meters

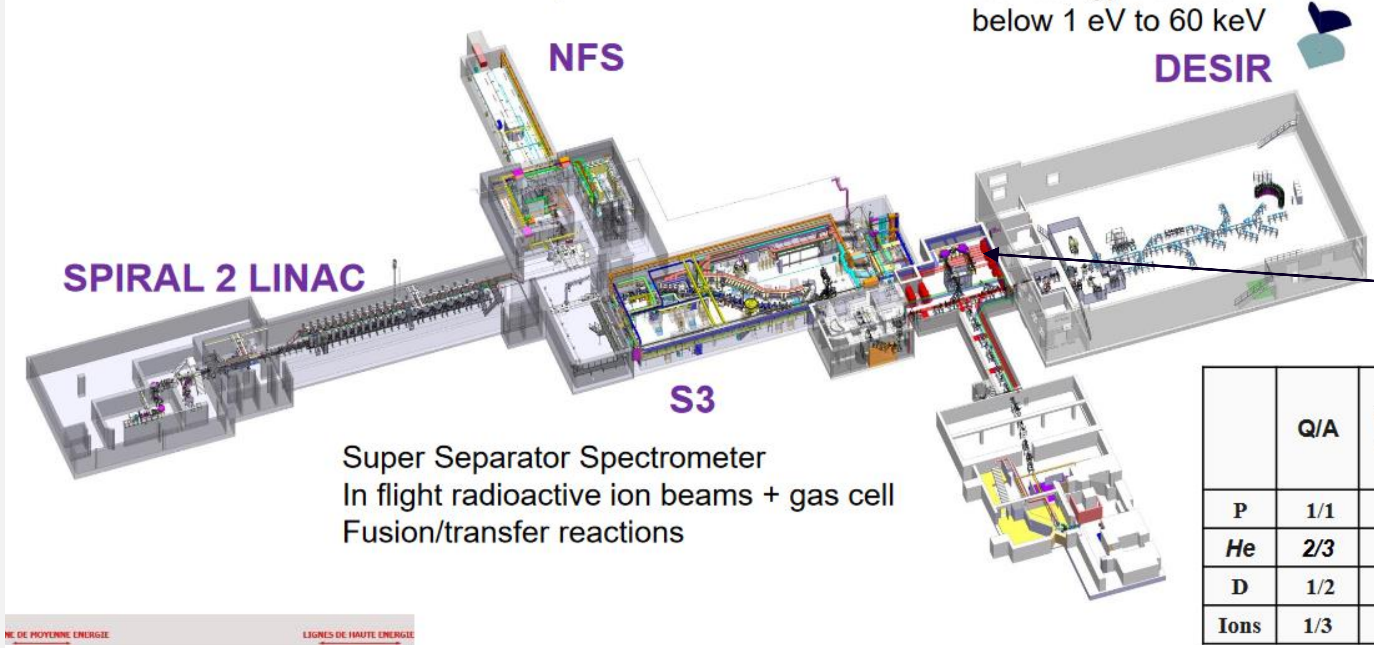
f [MHz]	101.28
Geometrical beta (β_g)	10.3
E_{acc} [MV/m]	6
Quality factor (Q_o) at E_{acc}	$5 \cdot 10^8$
Active length [m]	0.3
Beam aperture [cm]	2
Max. Transit Time Factor (TTF)	0.9

J.A. Rodriguez

GANIL-SPIRAL1-2

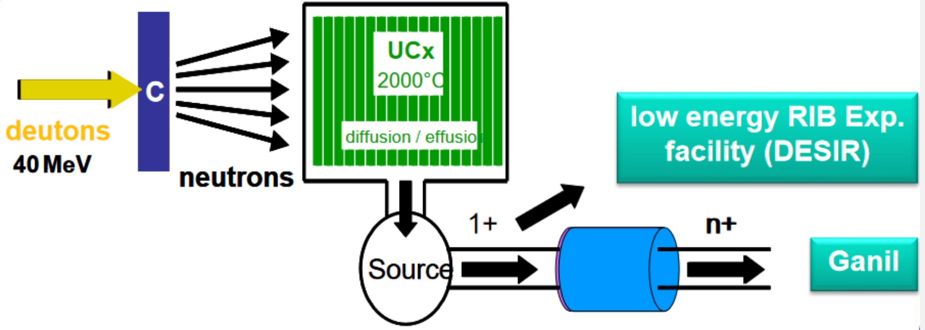
Neutron for Science
Neutrons up to 30 MeV

Experimental areas for very
low energy beams:
below 1 eV to 60 keV



Super Separator Spectrometer
In flight radioactive ion beams + gas cell
Fusion/transfer reactions

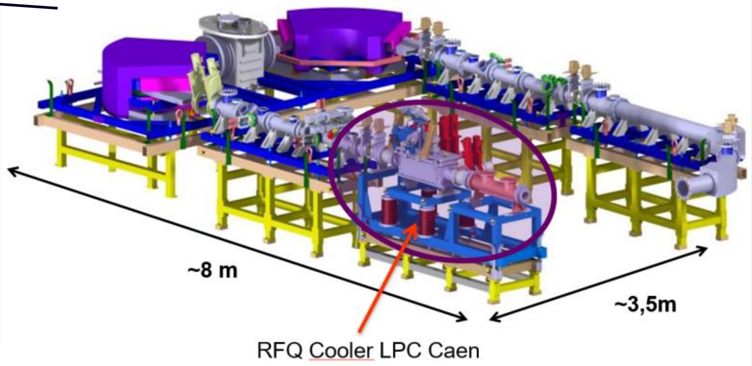
principle

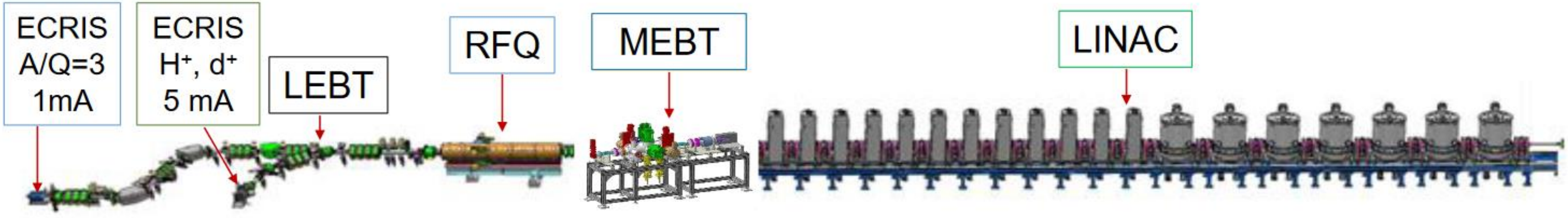


primary beams -> 5 mA
secondary beams -> 10^9 pps (Sn ^{132}) to 10^{12} pps (He)

	Q/A	I max (mA)	Energy (MeV/n)	CW max beam power (kW)
P	1/1	5	2 - 33	165
He	*2/3*	*1*	*2-2 4*	*36*
D	1/2	5	2 - 20	200
Ions	1/3	1	2 - 14.5	45

HRS





ECRIS
A/Q=3
1mA

ECRIS
H⁺, d⁺
5 mA

LEBT

RFQ

MEBT

LINAC

LNS

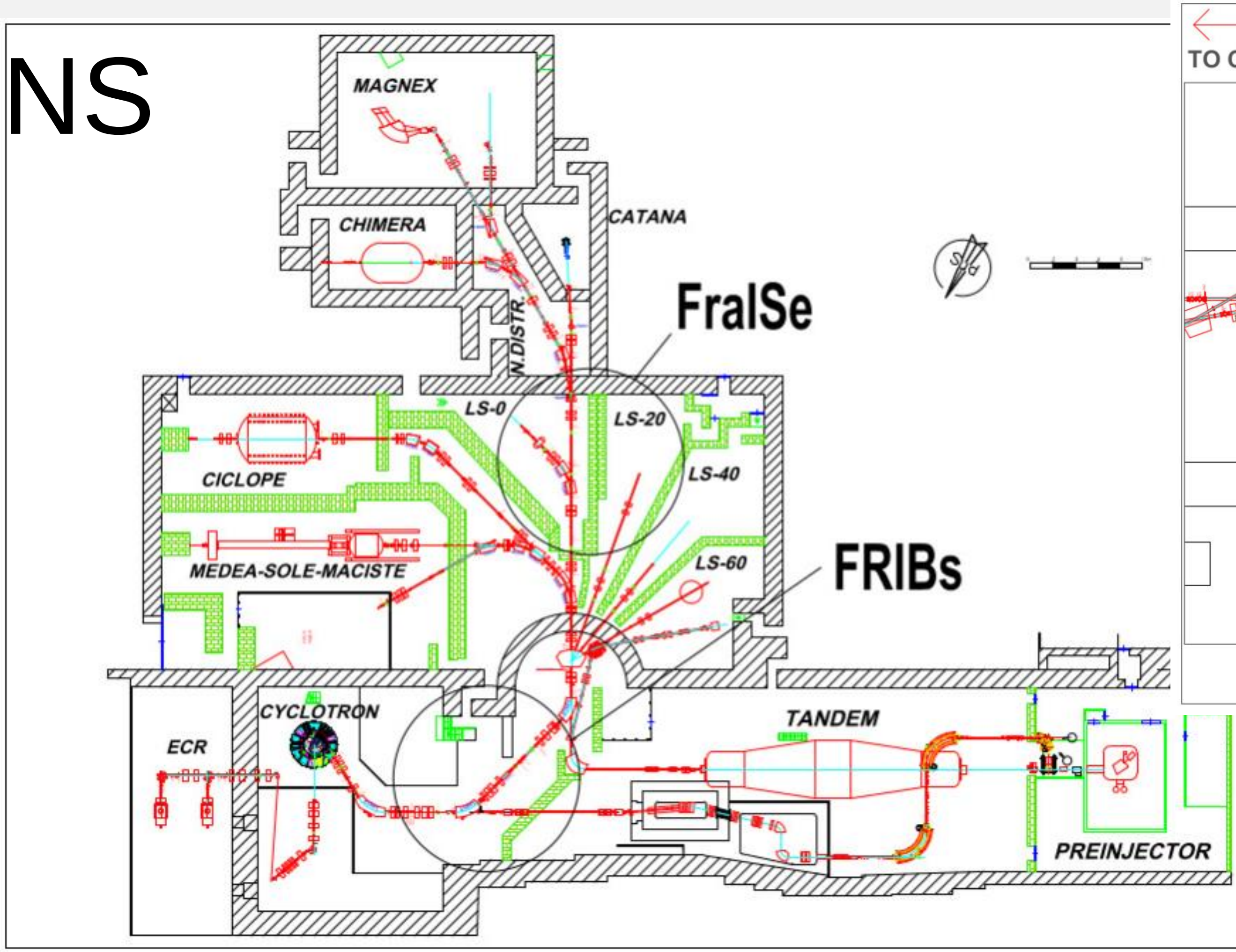
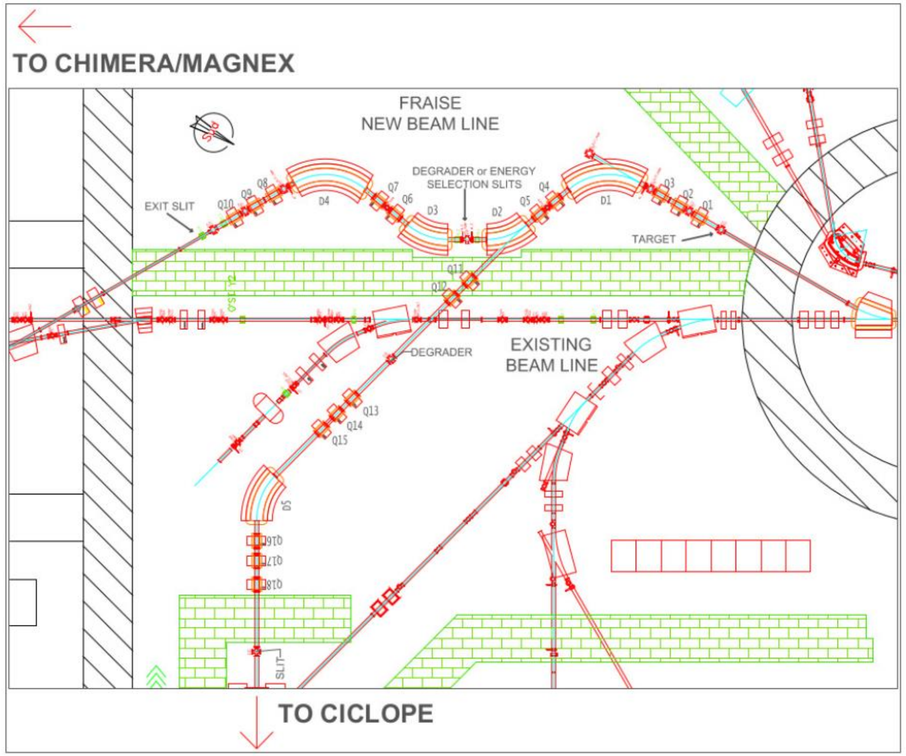


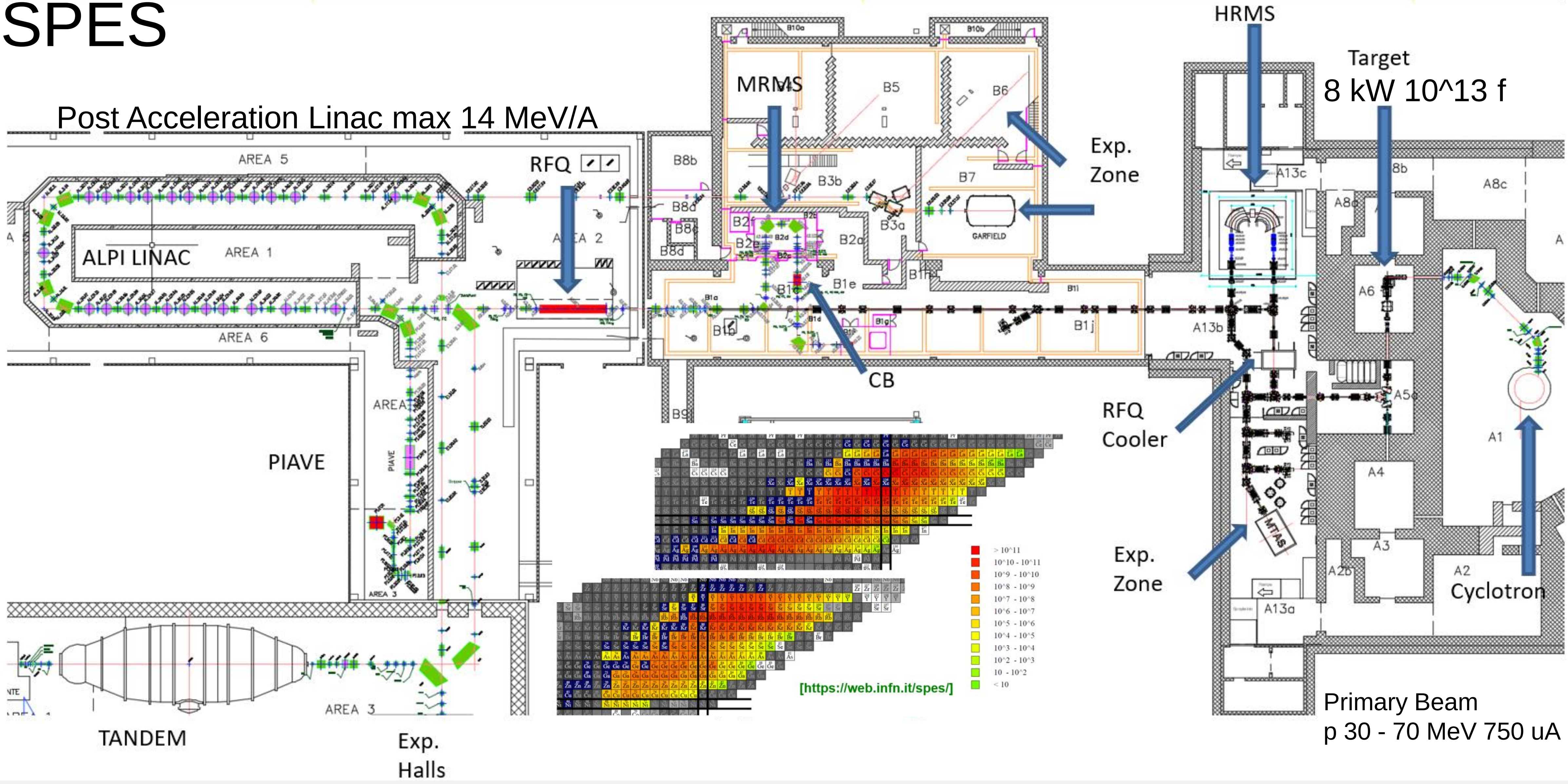
Figure 1. Schematic view of the INFN-LNS beam lines and halls. The position of the actual fragment separator, FRIBs, and of the new one, FraISe, are indicated by circles.



3. FRAISE: the new FRAgment In-fligth SEparator of INFN-LNS

In the forthcoming years, the Superconducting Cyclotron of the INFN-LNS is going to be renewed and improved [25]. One of the main novelties will be the replacement of the actual extraction system, based on electrostatic deflector, with a new extraction system based on stripping. Extraction by stripping is based on the sudden change of the magnetic rigidity of the accelerated ion, when its charge state is suddenly increased crossing a thin carbon foil. This method will be highly efficient for light ions; indeed, ions with mass number $A < 20$ and energy higher than 15 $AMeV$ are fully stripped, q=Z, with probability $> 99\%$ when crossing a stripper foil with equilibrium thickness [26]. However, the new extraction method will be very efficient also for medium mass nuclei up to $A \sim 40$. Intensities of the order of 10^{13} pps will be reached for beams, from C to Ar, at energies of $30 - 70$ $AMeV$; typical beam power will be of ~ 5 kW.

SPES



Post Acceleration Linac max 14 MeV/A

Target
8 kW 10^13 f

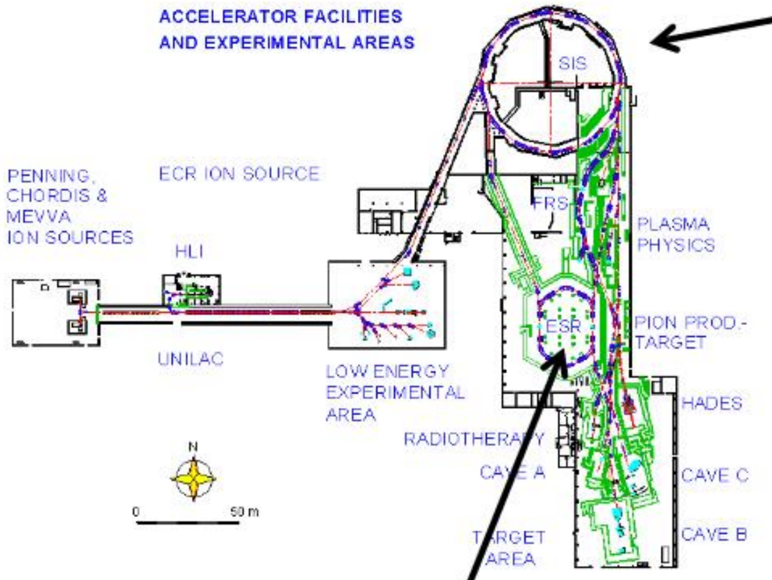
[https://web.infn.it/spes/]

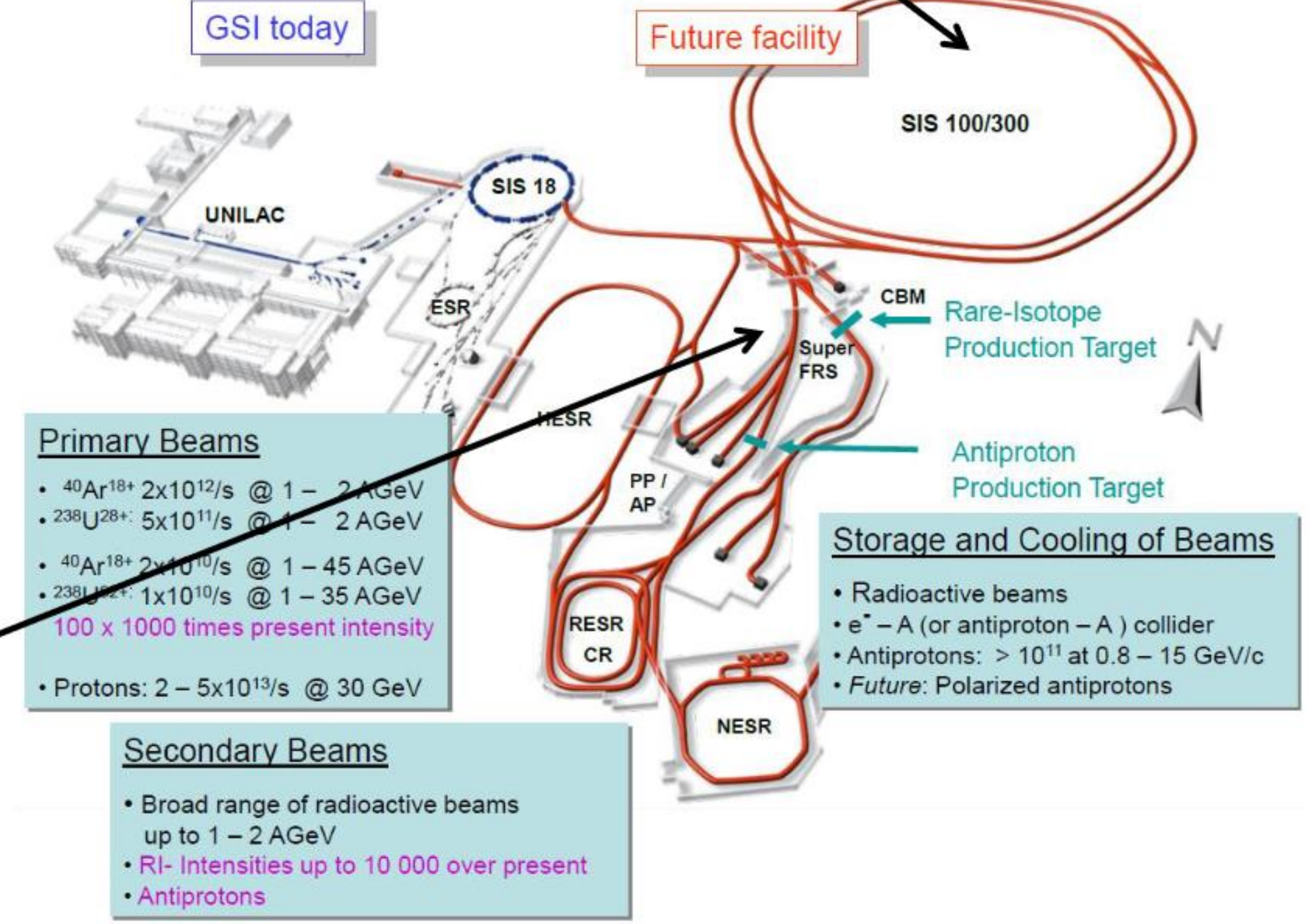
Primary Beam
p 30 - 70 MeV 750 uA

FAIR

SIS100	Protons	Uranium
Number of injections	4	4
Number of ions per cycle	2.5x 10^{13} ppp	5 x 10^{11}
Maximum Energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.7 Hz	0.7 Hz

Primary Beams





Primary Beams

- $^{40}Ar^{18+}$ $2x10^{12}$/s @ 1 – 2 AGeV
- $^{238}U^{28+}$: $5x10^{11}$/s @ 1 – 2 AGeV
- $^{40}Ar^{18+}$ $2x10^{10}$/s @ 1 – 45 AGeV
- $^{238}U^{92+}$: $1x10^{10}$/s @ 1 – 35 AGeV

100 x 1000 times present intensity

- Protons: 2 – $5x10^{13}$/s @ 30 GeV

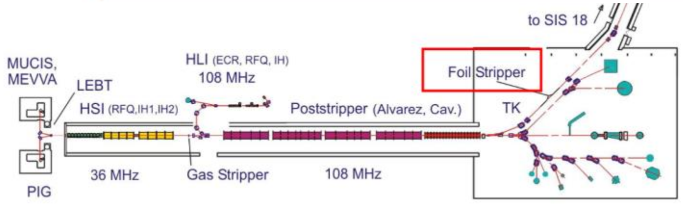
Storage and Cooling of Beams

- Radioactive beams
- e^- – A (or antiproton – A) collider
- Antiprotons: > 10^{11} at 0.8 – 15 GeV/c
- *Future*: Polarized antiprotons

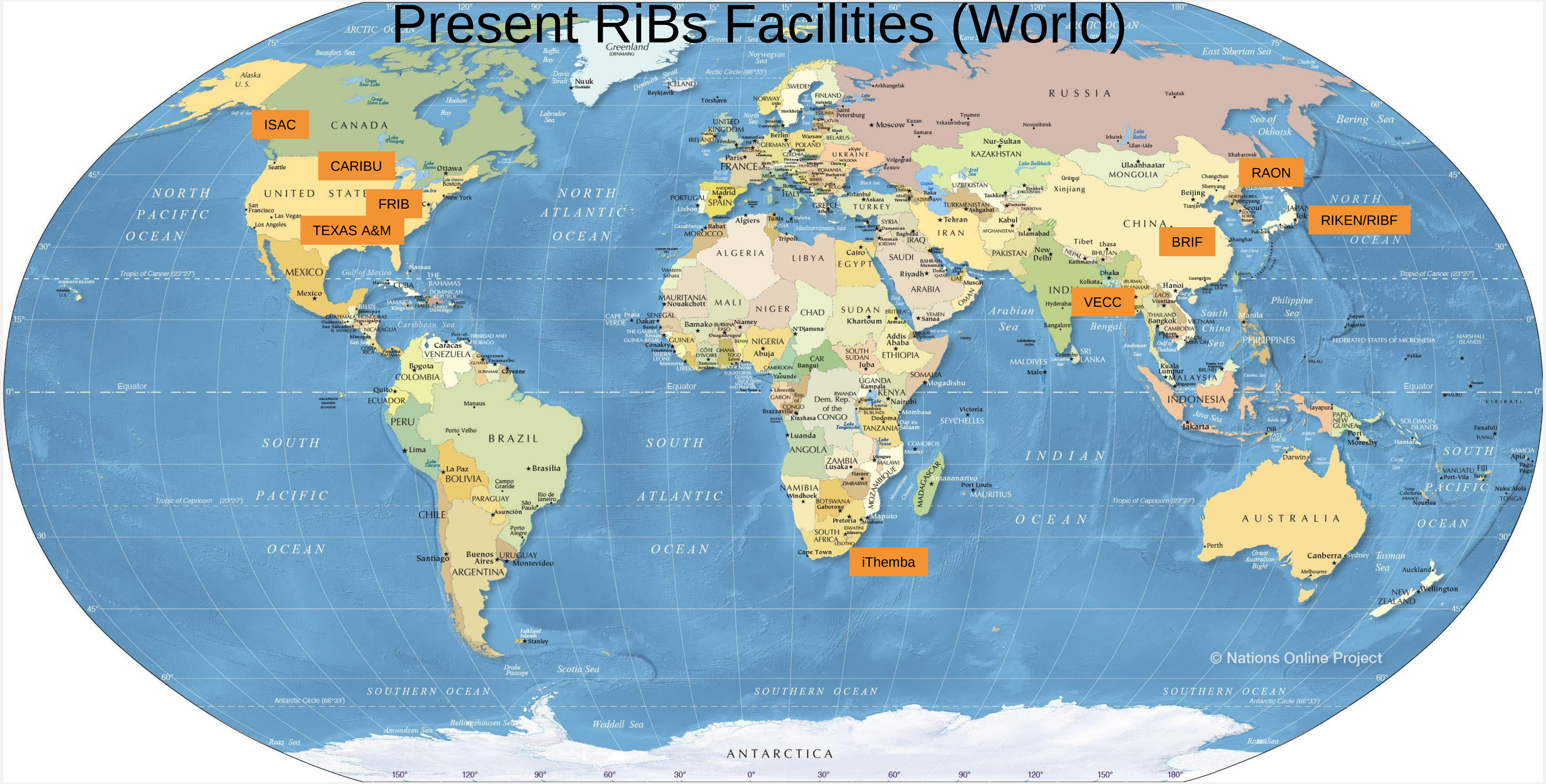
Secondary Beams

- Broad range of radioactive beams up to 1 – 2 AGeV
- RI- Intensities up to 10 000 over present
- Antiprotons

Secondary Beams



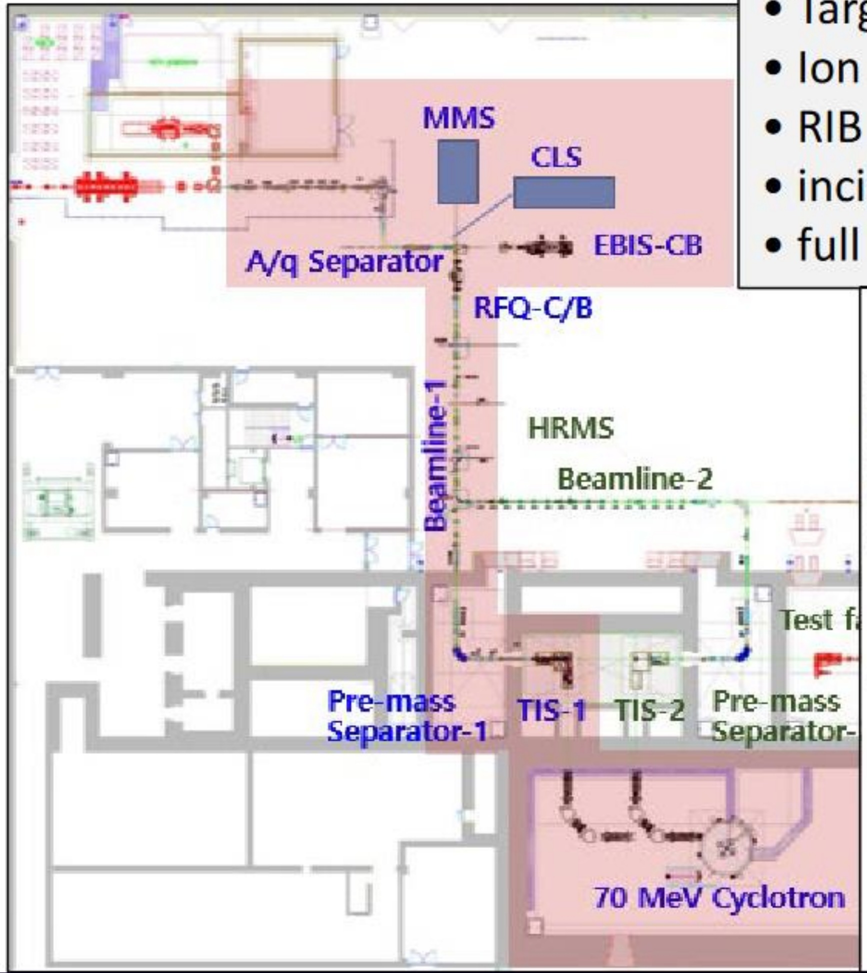
Present RiBs Facilities (World)

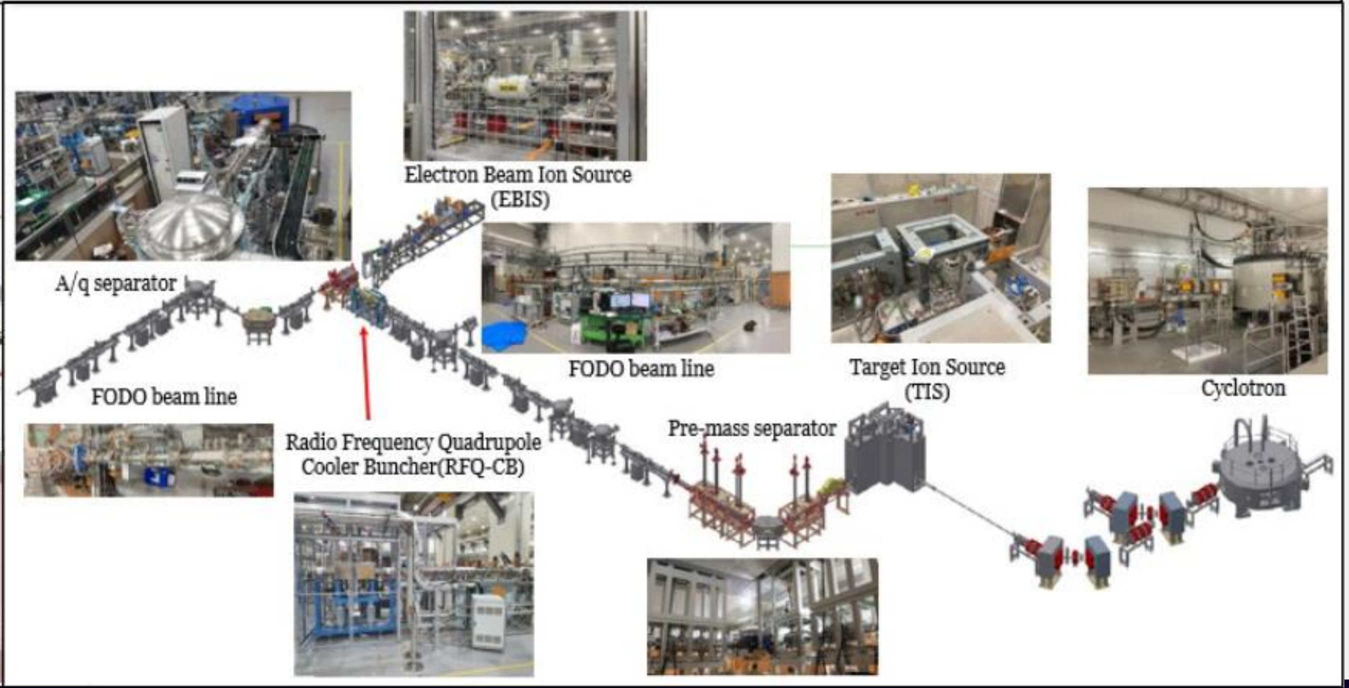


RAON

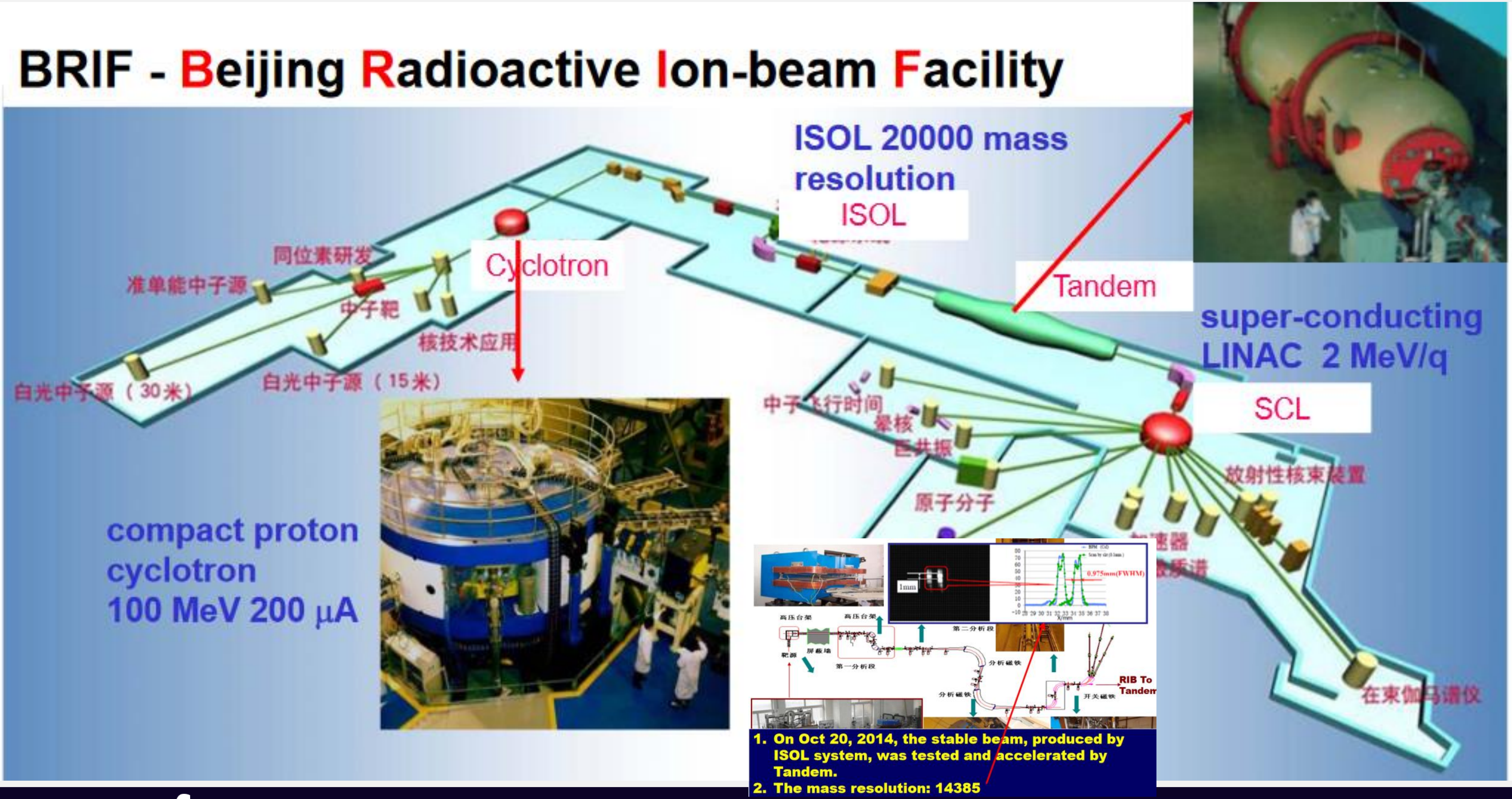
Target ion Source (20 keV, $^{132}Sn^{1+}$) → Pre-Separator ($m/\delta m = 400$) → RFQ Cooler (3πmm mrad, < 5ev) → EBIS (10 keV/u, $^{132}Sn^{33+}$) → Post linac (Charge state n+)

- Driver beam : proton 35<K<70 MeV, up to 70 kW
- Target : UCx, MgO, BN, CaO, BeO, SiC, etc
- Ion Source : Surface, RILIS, Plasma
- RIB : 6< A < 250, 10<K< 80 keV, 10^8 pps(Sn), >90% purity @Exp.
- incident to RFQ of Post accelerator 10 keV/u
- full remote maintenance system with TIS modularization





BRIF - Beijing Radioactive Ion-beam Facility



ISOL 20000 mass resolution

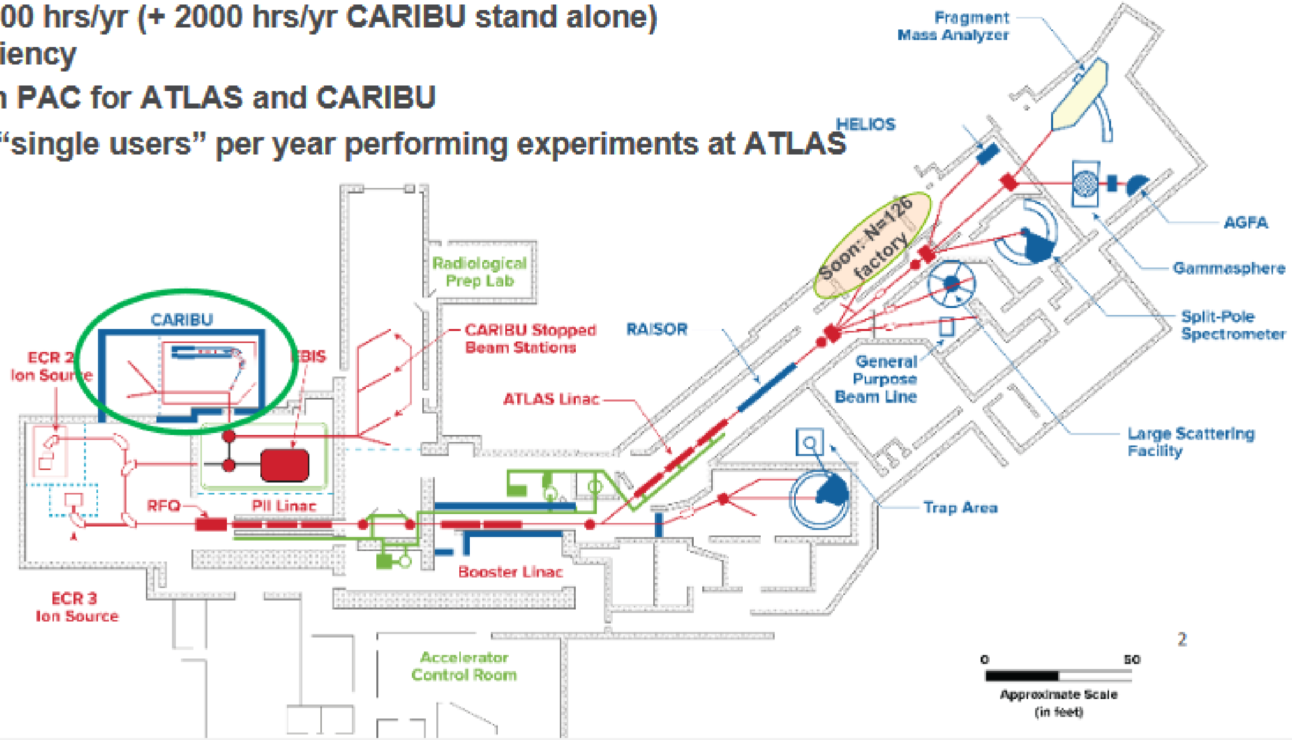
super-conducting LINAC 2 MeV/q

compact proton cyclotron
100 MeV 200 µA

1. On Oct 20, 2014, the stable beam, produced by ISOL system, was tested and accelerated by Tandem.
2. The mass resolution: 14385

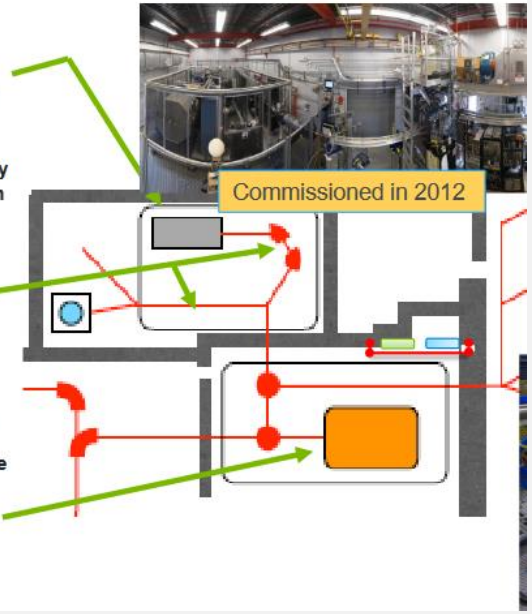
ATLAS/CARIBU FACILITY

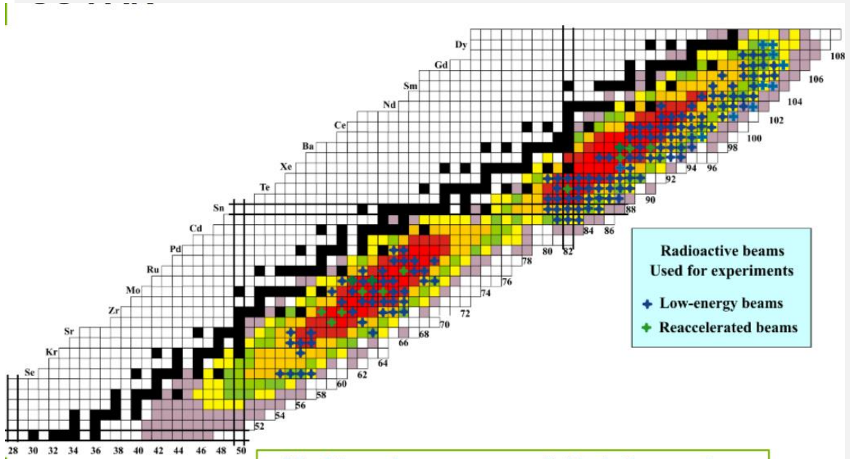
- ATLAS is the DOE nuclear physics stable beam national user facility
- Stable beams at high intensity and energy up to 10-20 MeV/u
- Light in-flight radioactive beams with RAISOR
  - *light beams, no chemical limitations, close to stability, acceptable beam properties*
- CARIBU beams
  - *heavy n-rich from Cf fission, no chemical limitations, low intensity, ATLAS beam quality, energies up to 15 MeV/u*
- State-of-the-art instrumentation for Coulomb barrier and low-energy experiments
- Operating ~6000 hrs/yr (+ 2000 hrs/yr CARIBU stand alone) at > 90% efficiency
  - Common PAC for ATLAS and CARIBU
  - 200-400 “single users” per year performing experiments at ATLAS



Main components of CARIBU

- **PRODUCTION**: “ion source” is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator and MR-TOF
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics





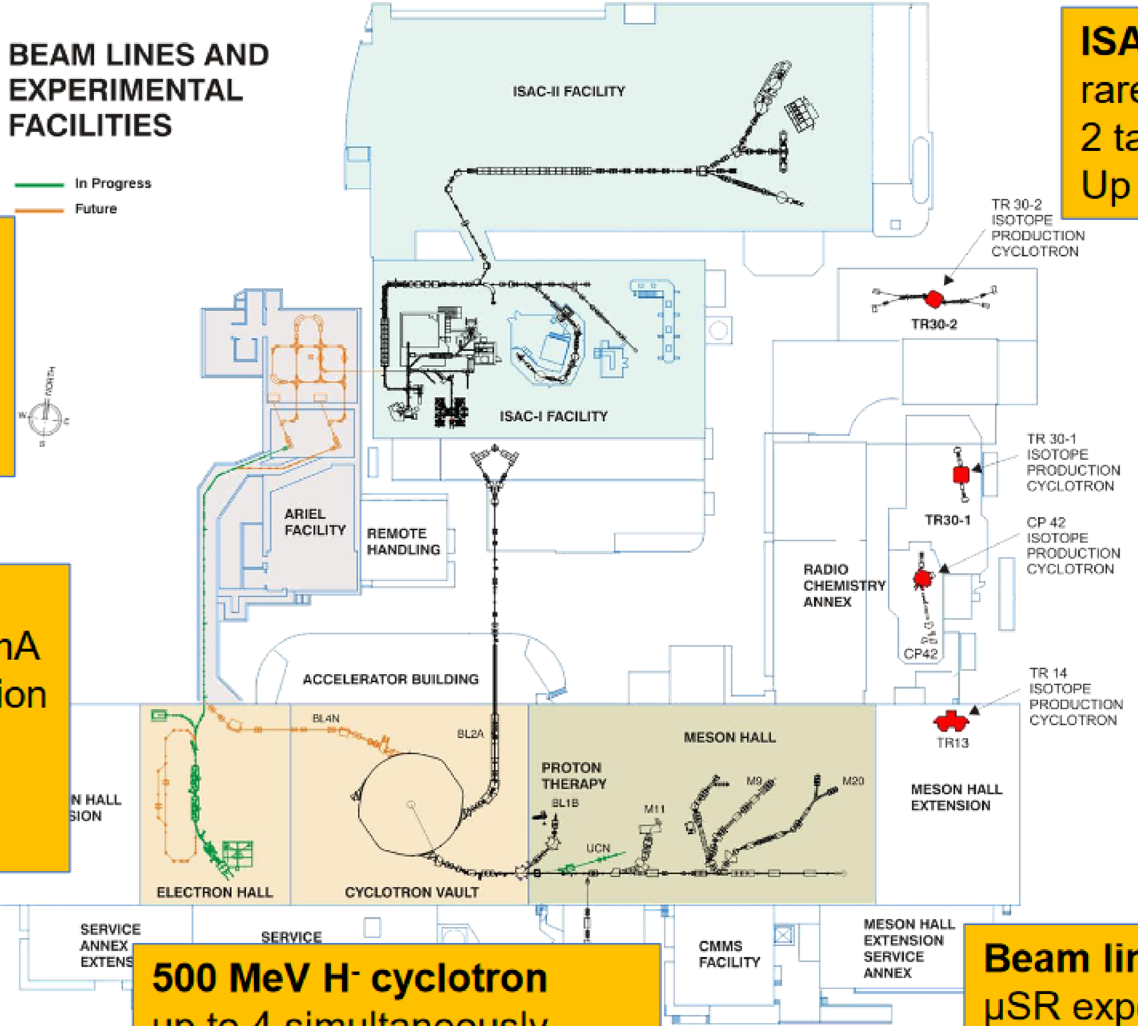
All of these beams now available in the new low-background low-energy area (Area 1)

TRIUMF

ISAC

CANREB
high resolution
mass separation
charge state breeding

ARIEL
e-linac 30 MeV 10 mA
e^- and p^+ target station
for rare isotope
beam production



500 MeV H- cyclotron
up to 4 simultaneously
extracted p^+ beams
individually variable energy
up to 120 μ A per beam line

ISAC I and II
rare isotope beams up to 15 MeV/u
2 target stations for
Up to 100 μA p beam @ 480 MeV

4 cyclotrons 13-30 MeV
for medical isotope production
(BWTX)

- More than 20 years radioactive beam delivery
- More than 800 isotopes
- Post-acceleration up to 15 MeV/u

- ECR charge state breeder at ISAC operational since 2008
  - isotopes from more than 15 elements have been charge bred so far
  - range of ions charge bred for acceleration: ^{21}Na – ^{160}Er
  - efficiency 1-5%

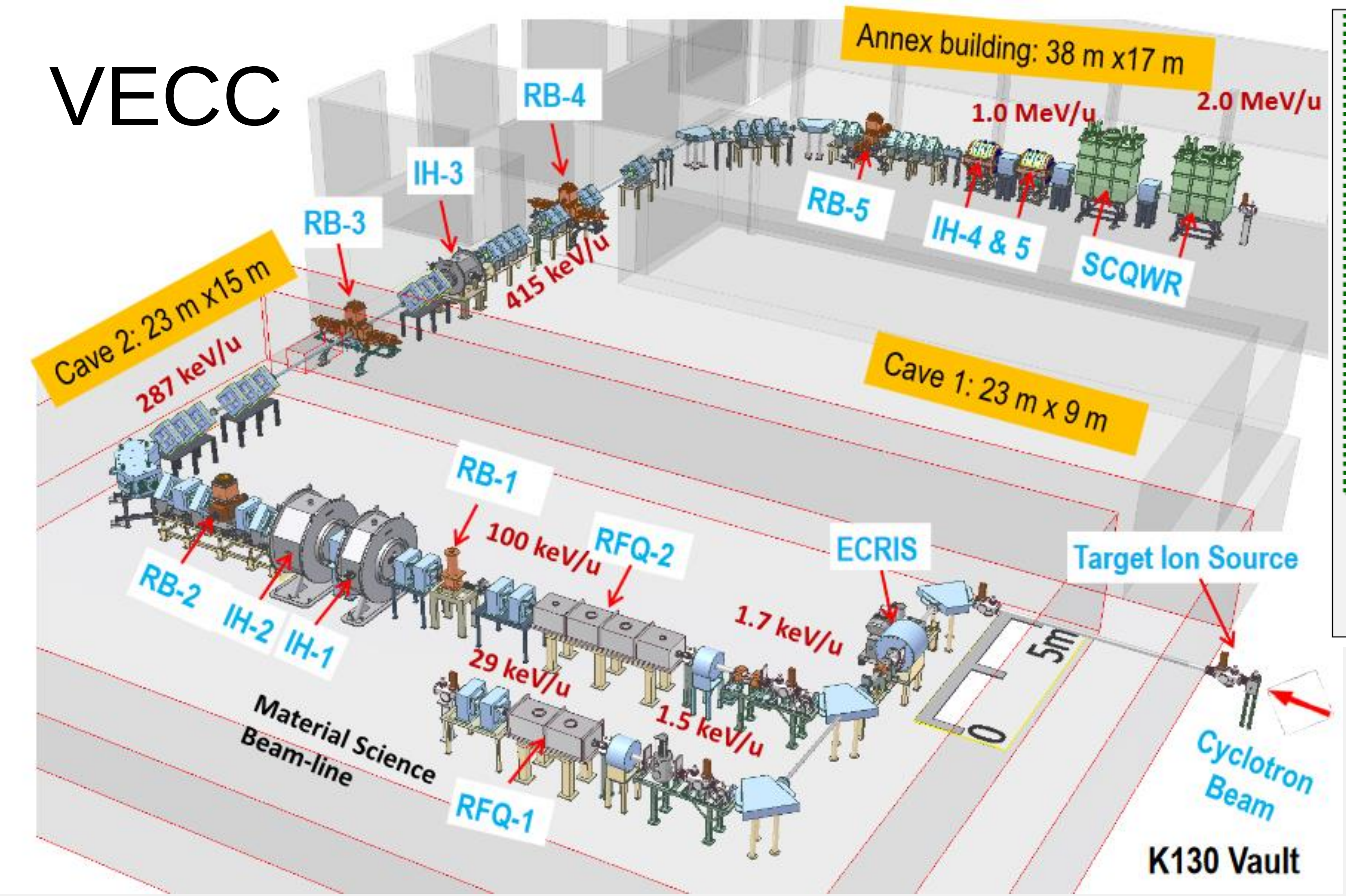
  - problems:
  - high background
  - long breeding time (~20 ms*q)

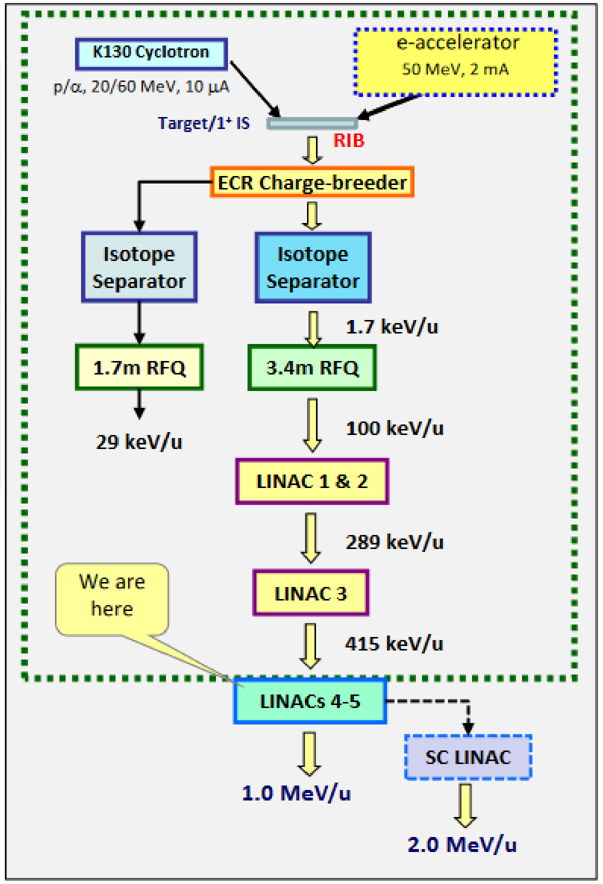
  - Ongoing improvements to ECR charge breeder:
  - implementing 2 frequency heating and improving injection/ extraction optics
  - → higher efficiency, higher charge states, more stable operation

Beam line 1
μSR experiments
isotope production
ultra cold neutron source
p and n irradiation
(p therapy)

2022-06-26

VECC





K130 Cyclotron
p/α, 20/60 MeV, 10 μA

e-accelerator
50 MeV, 2 mA

Target/1^+ IS

RIB

ECR Charge-breeder

Isotope Separator

Isotope Separator

1.7 keV/u

1.7m RFQ

3.4m RFQ

29 keV/u

100 keV/u

LINAC 1 & 2

289 keV/u

We are here

LINAC 3

415 keV/u

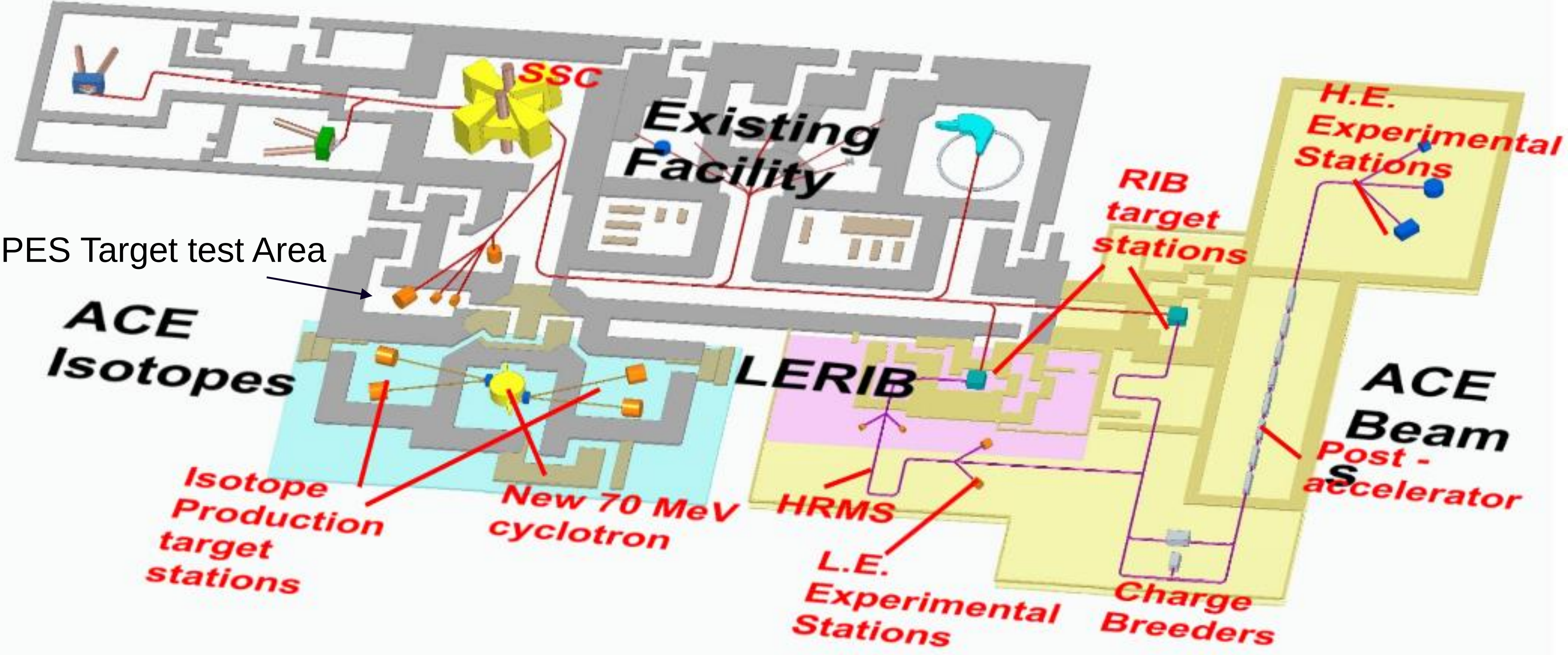
LINACs 4-5

SC LINAC

1.0 MeV/u

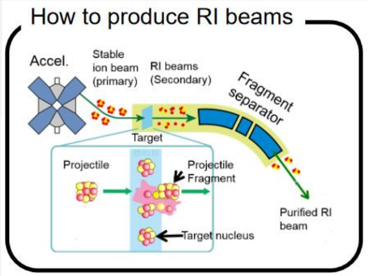
2.0 MeV/u

iThemba


SPES Target test Area

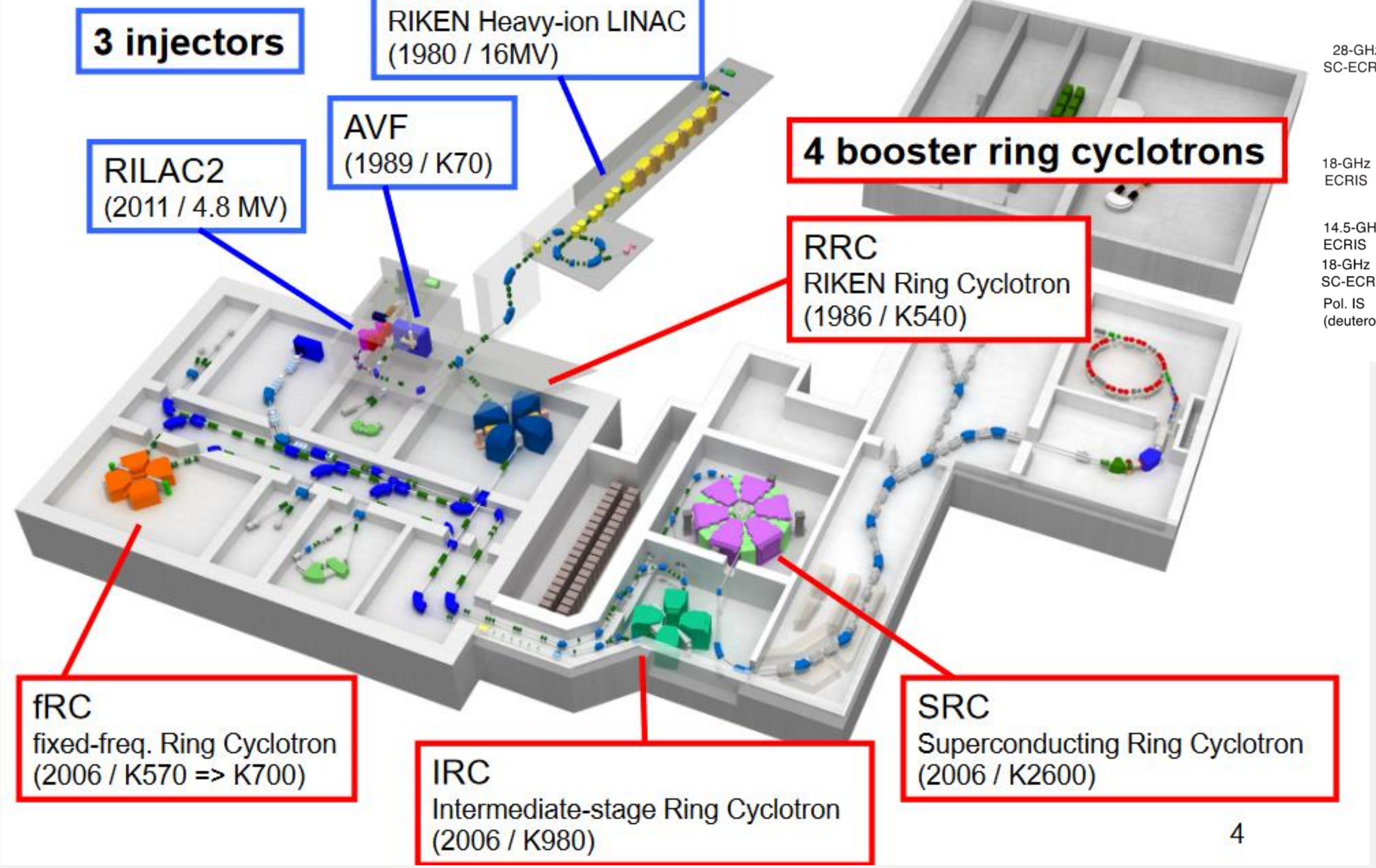
iThemba LABS (ACE Beams)	70 MeV	150 μA	10.5 kW	2×10^{13}
iThemba LABS (LERIB)	66 MeV	50 μA	3.3 kW	6.7×10^{12}

RIKEN/RIBS

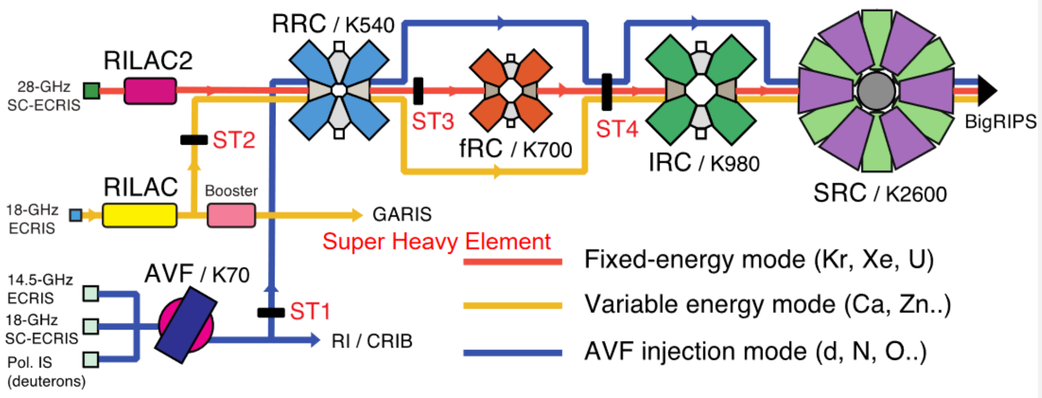


RIBF accelerators

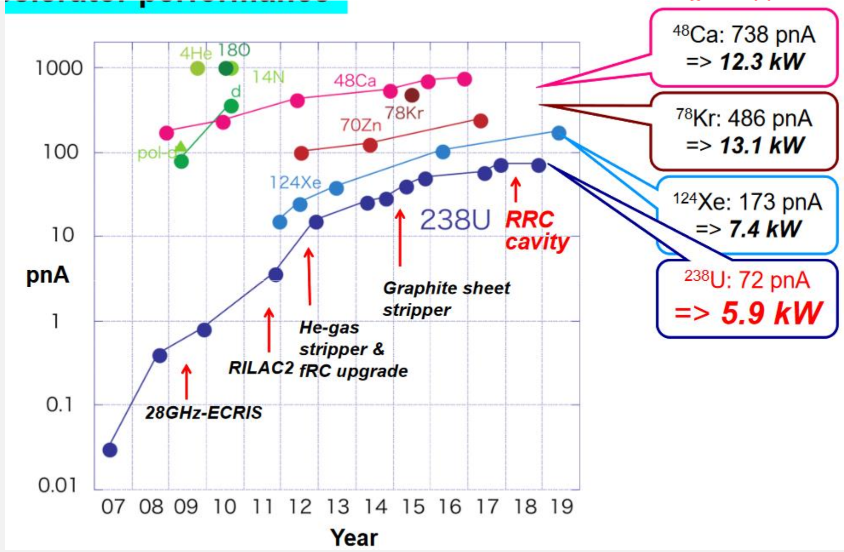
Y. Yano, NIM B261 (2007) 10



1) AVF-injection mode (< 440 MeV/u) : d, He, O, …
2) Variable-energy mode (< 400 MeV/u) : Ar, Ca, Zn, Kr, …
3) Fixed-energy mode (345 MeV/u) : Xe, U …



STn: charge stripper



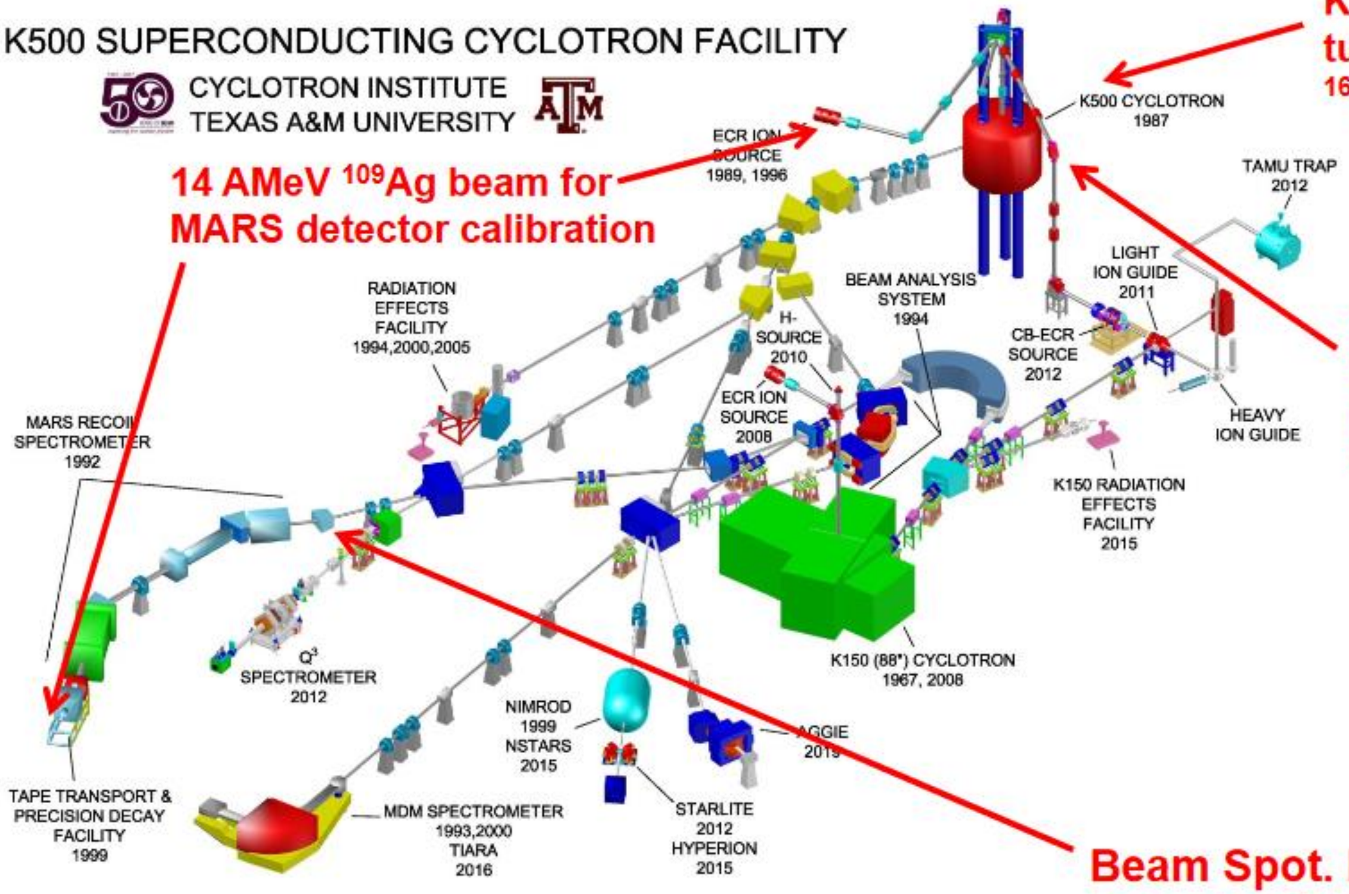
^{48}Ca: 738 pnA => ***12.3 kW***

^{78}Kr: 486 pnA => ***13.1 kW***

^{124}Xe: 173 pnA => ***7.4 kW***

^{238}U: 72 pnA => ***5.9 kW***

Tuning the K500 and its beam-lines for the ^{112}In RIB



14 AMeV ^{109}Ag beam for MARS detector calibration

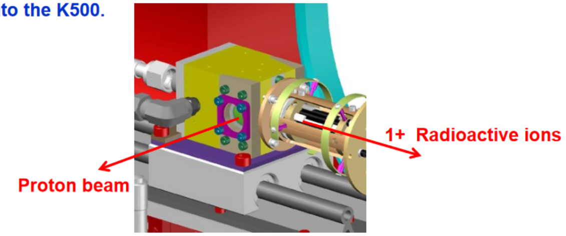
Change the K500 field and tune14 AMeV ^{16}O^{3+} (.18758)

Change only the RF by +6.5 KHz for 14 AMeV ^{112}In^{21+} (.18768)

Beam Spot. Here the beam is stripped for injection into MARS.

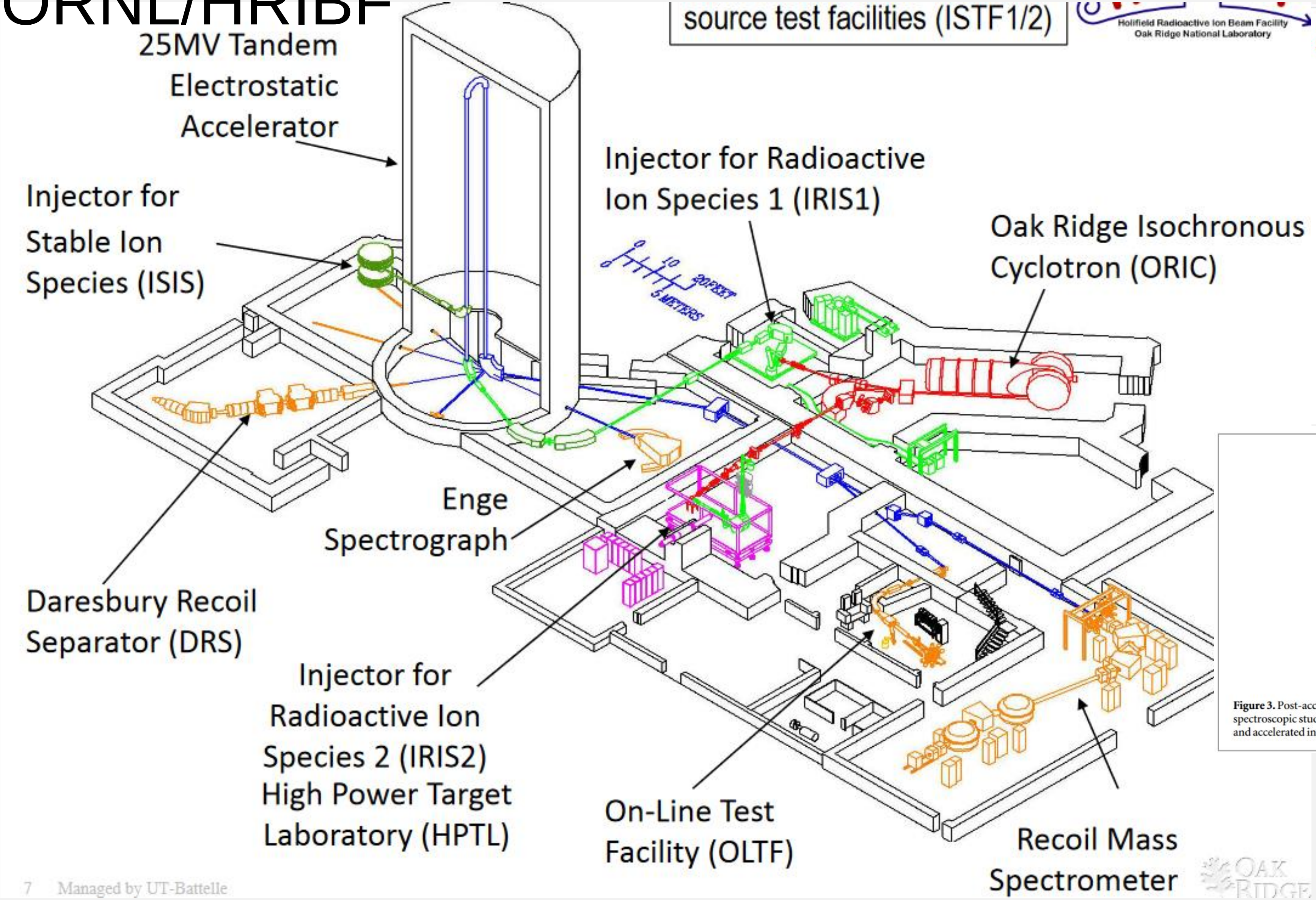
RIB Production via Light-Ion Guide

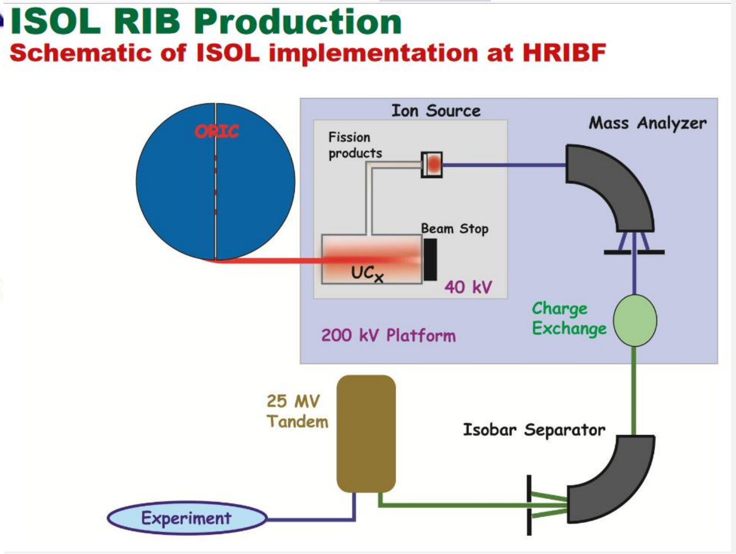
- The K150 provides an intense beam of light ions (p, d, ^{3}He, α) to a target mounted on the side of the LIG chamber.
- Products from the target directly enter a helium gas flow.
- Products in the chamber are stopped by the helium, remain singly charged, and are guided by the helium flow through an aperture of one to two millimeters diameter.
- For K500 acceleration the low-charge-state beam of products is transported to the CB-ECRIS. In the ECRIS the products are stopped in the plasma and further ionized by the energetic electrons.
- Extracted beam from CB-ECRIS is analyzed, and a beam of one charge-state is injected into the K500.



- How much ^{112}In did we make (best result) ?
  - 0.3 (MARS)*0.1 (K500) estimated transport to end of MARS for ^{112}In^{39+}
  - If 100 particle/sec observed at MARS, implies ~ $3*10^3$ p/s ^{112}In^{21+} after CB-ECR.
- For ^{112}In, we were limited to about 2 μA protons on target (water leak). ~10x more beam now available.
- Estimate 10^3 p/s re-accelerated (after K500) in reach for ^{112}In.
- Will soon try other beams with > 100 mb cross- section and need to work towards lighter nuclei. Some possible beams:
  - ^{57}Ni – from ^{58}Ni(p,d), E_p = 26 MeV – σ (TALYS) = 293 mb.
  - ^{45}Ti – from ^{46}Ti(p,d), E_p = 26 MeV – σ (TALYS) = 455 mb.
  - ^{30}P – from ^{27}Al(α,n), E_α = 11 MeV – σ (TALYS) = 200 mb.
  - ^{34}Cl – from ^{35}Cl(p,d), E_p = 24 MeV – σ (TALYS) = (g+m) (83+119) mb.
  - ^{37}Ar – from ^{37}Cl(p,n), E_p = 9 MeV – σ (TALYS) = 465 mb.

ORNL/HRIBF




ISOL RIB Production

Schematic of ISOL implementation at HRIBF

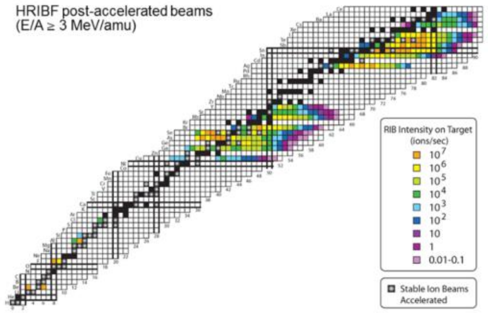
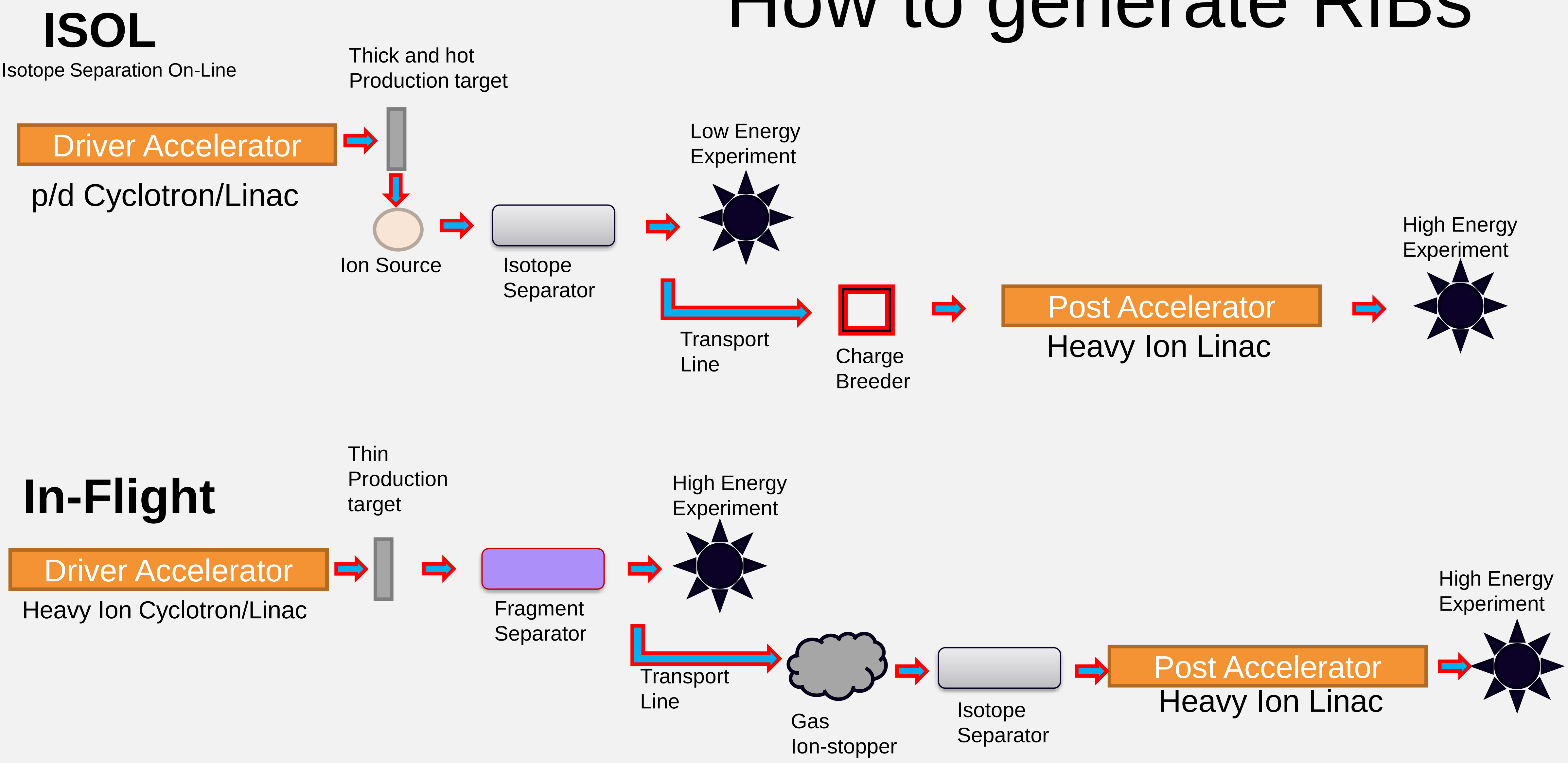


Figure 3. Post-accelerated radioactive and stable ion beams that were available at the HRIBF for a variety of nuclear reactions and spectroscopic studies [12]. About 80 stable isotopes from 39 elements were also produced as negative ions with a Cs-sputter ion source and accelerated in the tandem for nuclear physics experiments. Reproduced from [12]. © IOP Publishing Ltd. All rights reserved..

Facilities overview

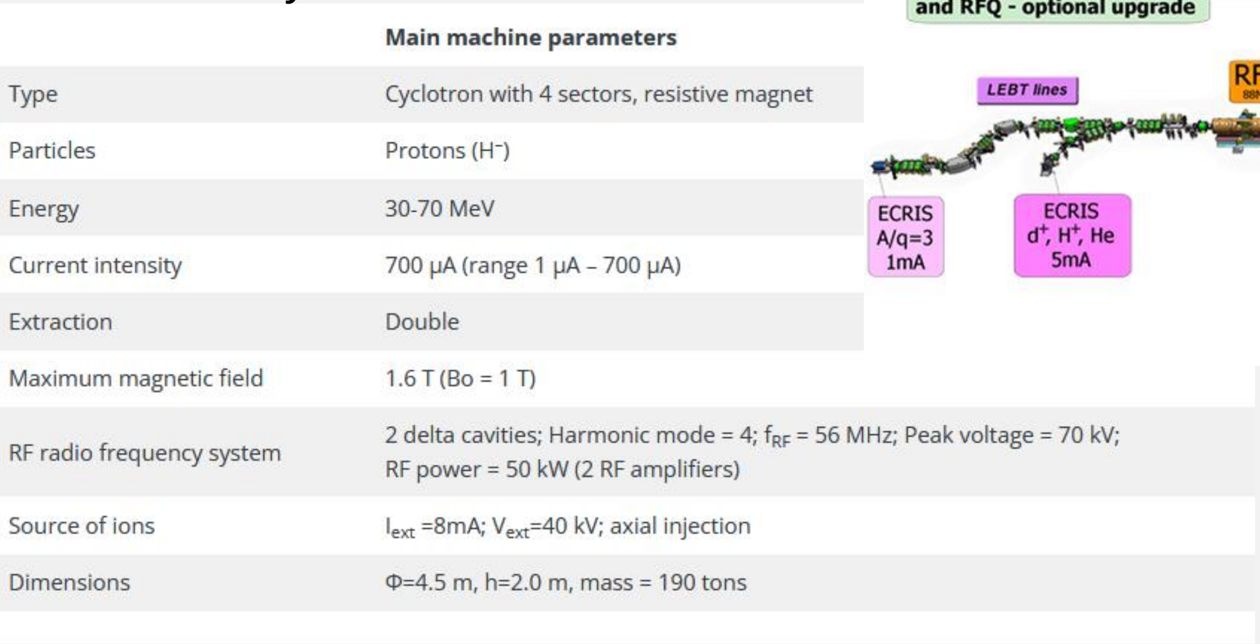
Facility	Method	Driver Acc	Post Acc	Status	Fission/s (total)	Resolution	Target
CERN/ISOLDE	ISOL	p (PS Ring)	SC-Linac	Operating	10^12 (1/uC)	1/20000 (HRS)	Various Direct
GANIL/SPIRAL2	ISOL	d (Linac)	Cyclotron	Future	10^12	1/20000 (DESIR)	Two Stage n->UCx
LNL/SPES	ISOL	p (Cyclotron)	SC-Linac	Future	10^13	1/20000 (HRMS)	Various/UCx Direct discs
GSI/FAIR	In-Flight	Ions (SIS Ring)	Ring	Future	10^12 (U SIS100)	1/1500 (dp/p)	Gas/foil stripper
MSU/FRIB	In-Flight	Ions (Linac)	SC-Linac	Commissioning	10^7 (to experiment)	1/1720 (dp/p)	Liquid Stripper
IBS/RAON	ISOL	p (Cyclotron)	SC-Linac	Commissioning	10^8	1/10000 (dp/p KOBRA)	Ucx Direct
CIAE/BRIF	ISOL	p (Cyclotron)	Tandem+SC-Linac	Commissioning	10^6	1/20000	MgO Direct
ANL/CARIBU	ISOL	-	SC-Linac	Operating	10^7	1/10000	252Cf source
TRIUMF/ISAC	ISOL	p (Cyclotron) e (Linac)	SC-Linac	Operating	10^13 (ARIEL)	1/20000	Various Direct discs
HBNI/VECC	ISOL	p (Cyclotron)	SC-Linac	Commissioning	10^4	HRS	Various Direct
NRF/iThemba	ISOL	p (Cyclotron)	Linac	Future	10^13	HRS	Various Direct
RIKEN/Ribs	In-Flight	Ions (Cyclotrons)	Cyclotron	Operating	10^12	1/3300 (dp/p)	Gas/Rotating stripper
Texas/A&M	ISOL	p (Cyclotron)	Cyclotron	Operating	10^4	-	Gas He Direct
ORNL/HRIBF	ISOL	p (Cyclotron)	Tandem	Operating	10^7	1/3000	Ucx Direct

How to generate RiBs



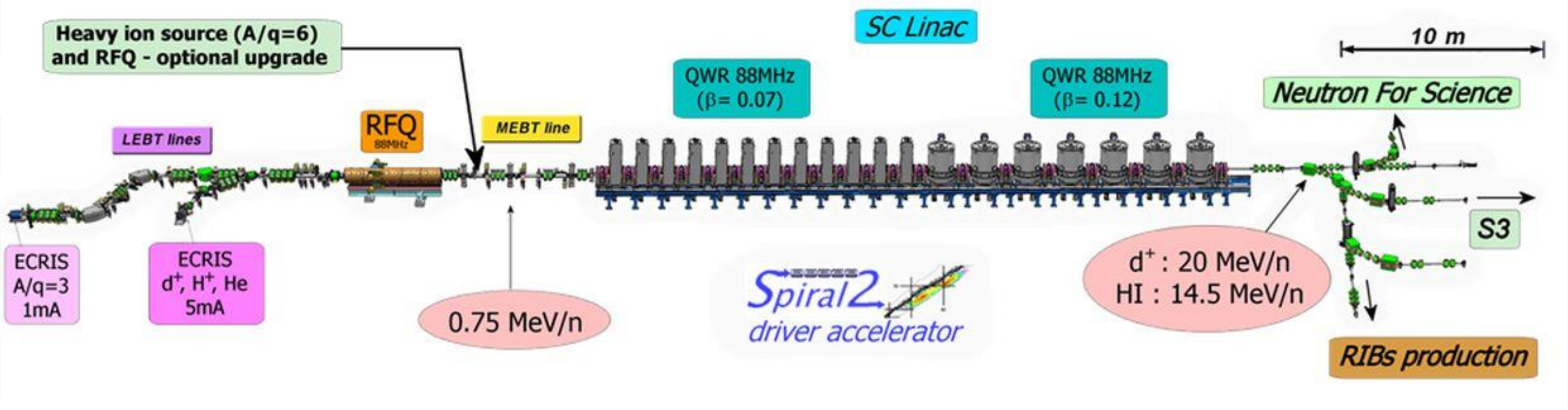
DRIVER Accelerator for the Primary beam

SPES Cyclotron

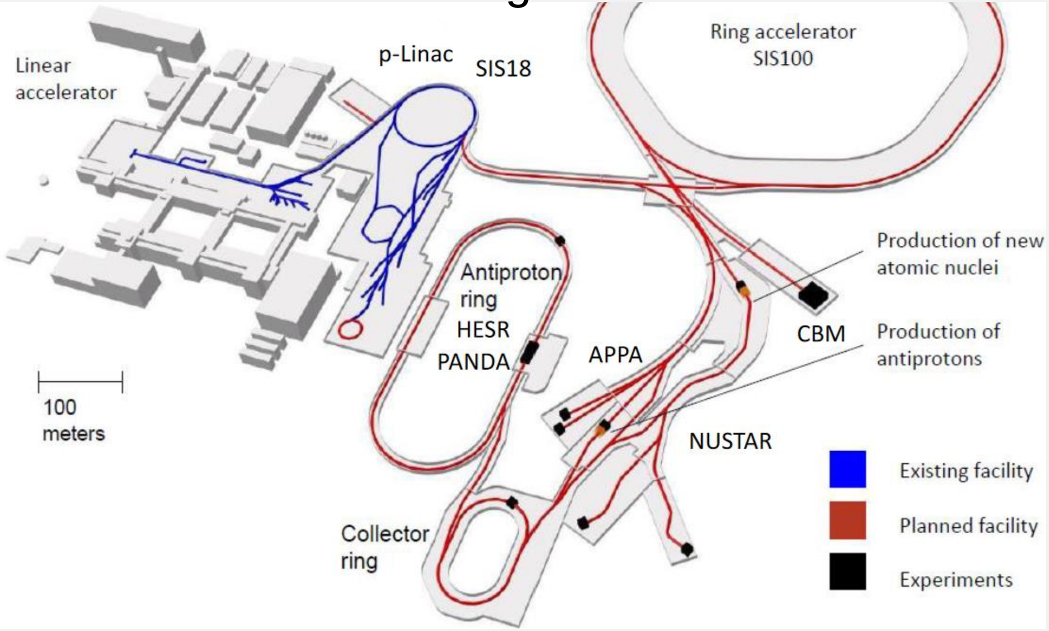


	Main machine parameters
Type	Cyclotron with 4 sectors, resistive magnet
Particles	Protons (H^-)
Energy	30-70 MeV
Current intensity	700 µA (range 1 µA – 700 µA)
Extraction	Double
Maximum magnetic field	1.6 T (Bo = 1 T)
RF radio frequency system	2 delta cavities; Harmonic mode = 4; f_{RF} = 56 MHz; Peak voltage = 70 kV; RF power = 50 kW (2 RF amplifiers)
Source of ions	I_{ext} =8mA; V_{ext}=40 kV; axial injection
Dimensions	Φ=4.5 m, h=2.0 m, mass = 190 tons

Spiral2 Linac

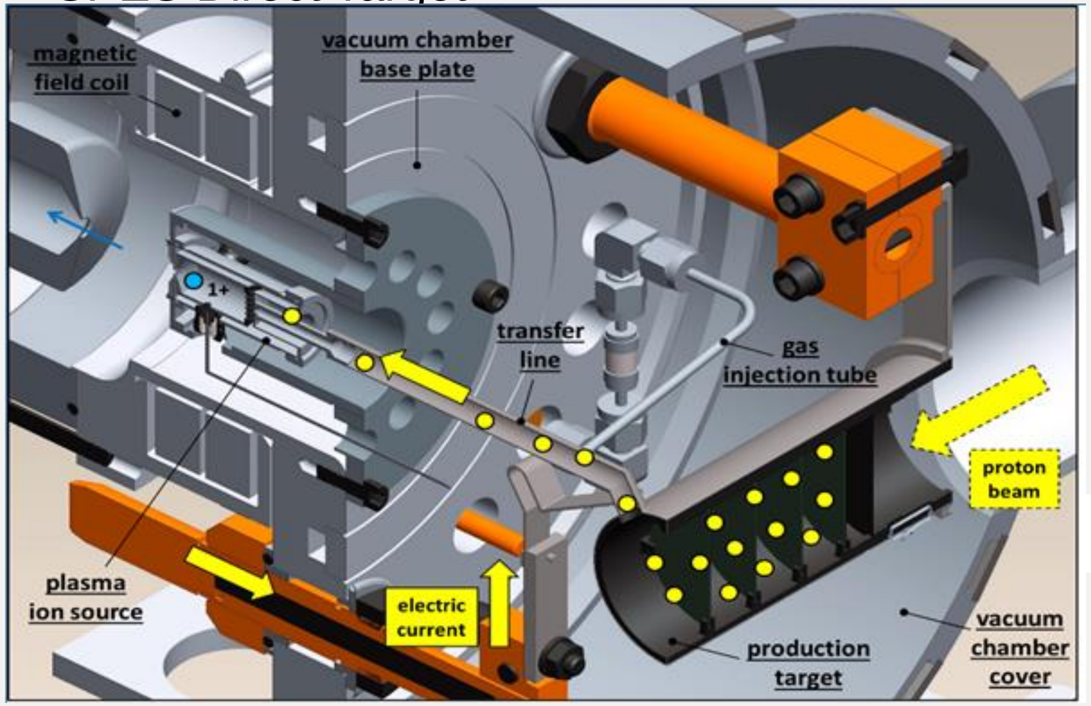


FAIR rings



TARGET

SPES Direct Target



Beam test at iThemba lab. (2014): 66MeV protons, 60 μA on full scale SiC prototype at 1600 ^{o}C (FEM sim. Validation)
Former beam tests: ORNL (2007, 2010-2011) SiC, Ucx;
ISOLDE(2009) UCx, IPNO (2013) UCx.

SPIRAL2 Neutron Converter

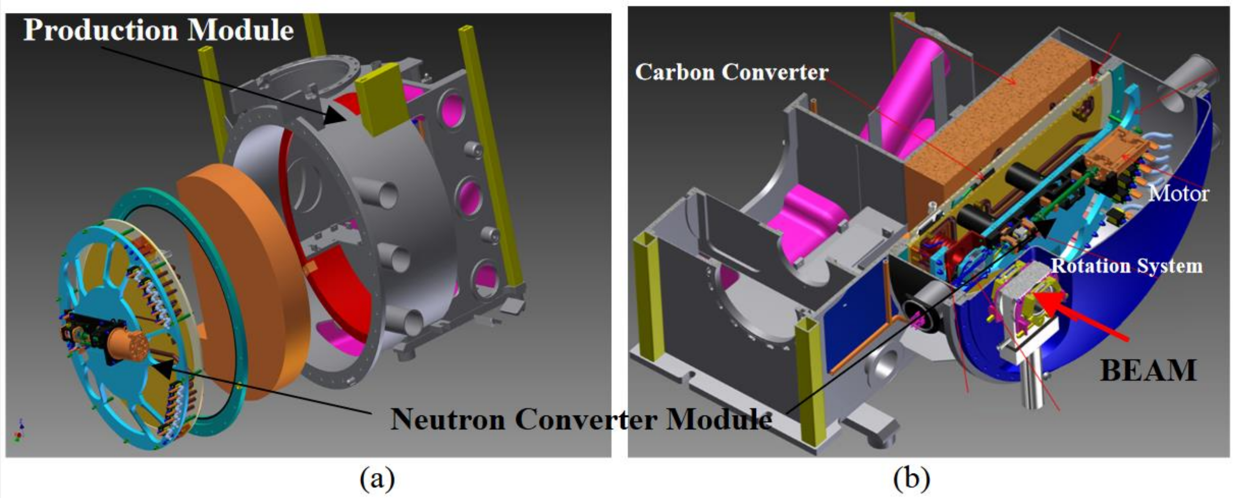
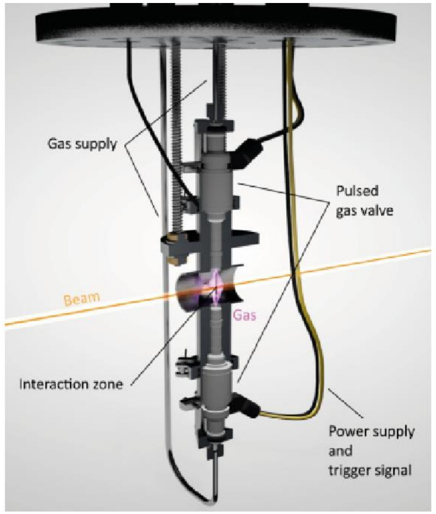
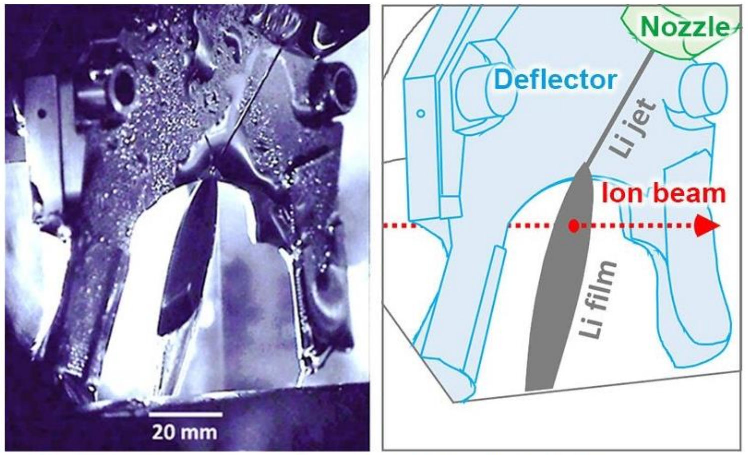


FIGURE 2. Neutron Converter Production Module.
(a) Assembly Explode View. (b) Neutron Converter, Transversal Section.

FAIR: H2 gas-cell stripper



FRIB: Li liquid stripper

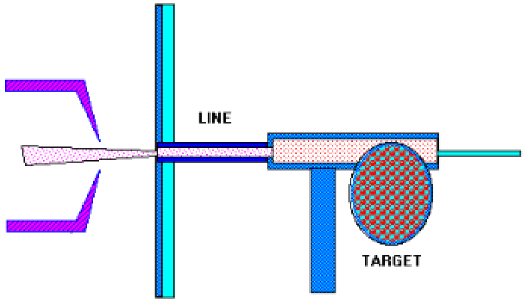


Left: Photograph of the liquid-lithium film formed in the FRIB beamline chamber. The extremely smooth surface of the lithium film appeared as a mirror. Right: Corresponding illustration with labels for clarity.

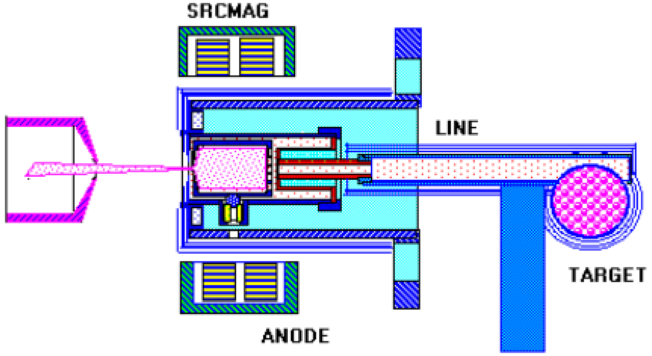
Image courtesy of the Facility for Rare Isotope Beams

1^+ ion-sources

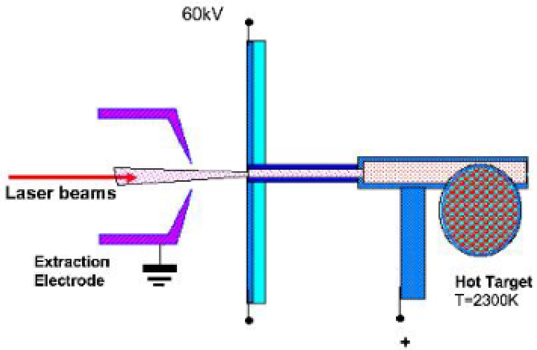
Surface ion source

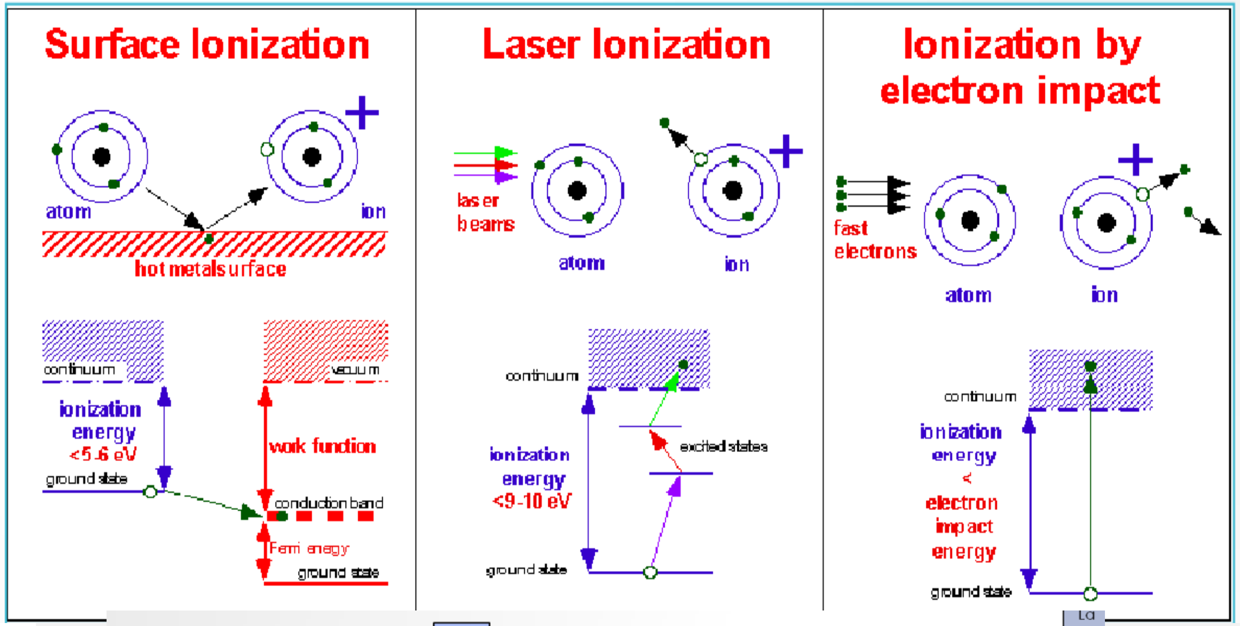


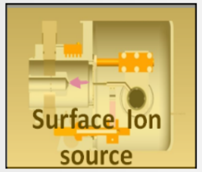
Plasma ion source

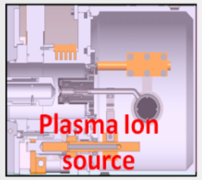


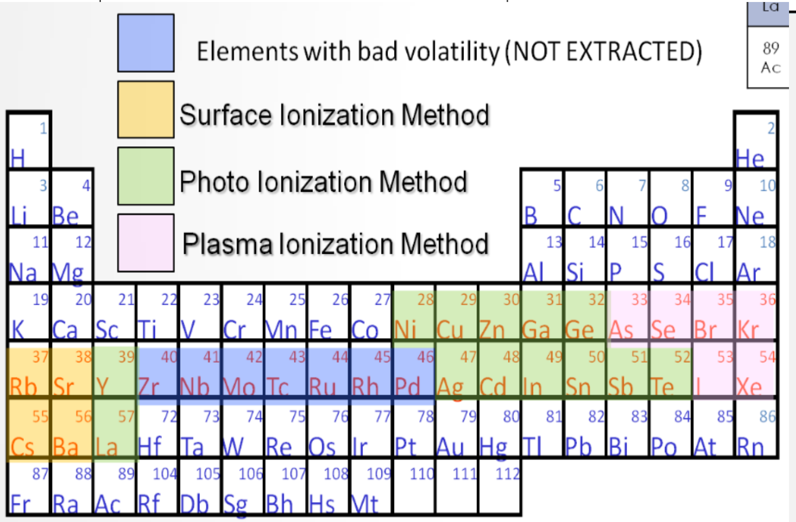
Laser ion source











🟦 Elements with bad volatility (NOT EXTRACTED)

🟨 Surface Ionization Method

🟩 Photo Ionization Method

🟪 Plasma Ionization Method

Main fission (p-> ^{238}U) fragments

SPECTROMETER (low energy) U shape

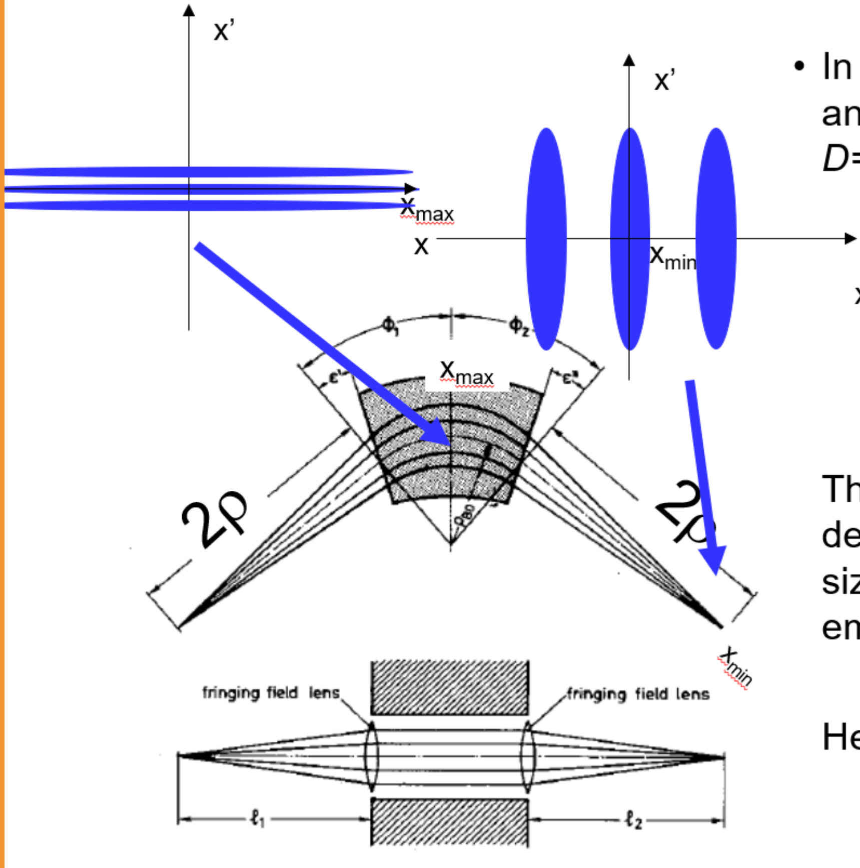


Fig. 4.8. A stigmatic focusing homogeneous sector field using the fringing field *y* focusing of inclined field boundaries.

- In the specific case of $\phi=90^0$, edge angle of 26.6^0, momentum dispersion $D=4\rho$ for stigmatic optics. Since $eB\rho=p$

$$\frac{\Delta p}{p}=\frac{2x_{\min}}{D}=\frac{x_{\min}}{2\rho}$$

$$\frac{\Delta m}{m}-\frac{\Delta w}{w}=2\frac{\Delta p}{p}=\frac{x_{\min}}{\rho}$$

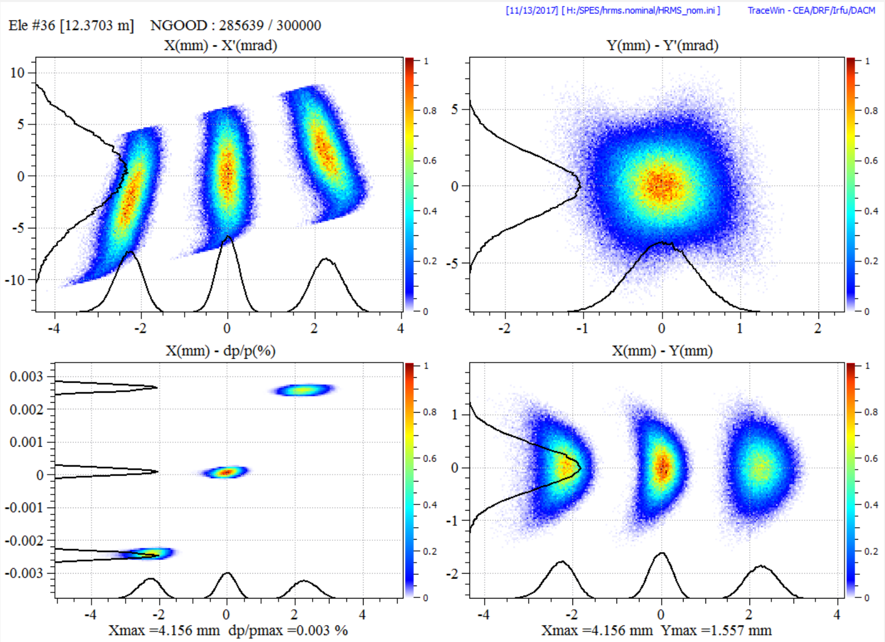
The spot size at analysis is determined by beam maximum beam size in the magnet and beam emittance.

$$x_{\min}x_{\max}=4\varepsilon_{geom}\rho$$

Hence

$$\boxed{\frac{\Delta m}{m}=\frac{4\varepsilon_{geom}}{x_{\max}}-\frac{\Delta w}{w}}$$

- While geometrical aberrations depends on x_{max}/ρ



Role of systematic errors

- For the high resolution separators is extremely important the effect of the external errors (static or dynamic)*

$$\frac{\Delta m}{m}-\left[\frac{\Delta V}{V}+2\frac{\Delta B}{B}+2\frac{\Delta\rho}{\rho}\right]=\underbrace{4\frac{x_{\min}}{D}+\frac{\Delta w}{w}}$$

Accelerator voltage stability
Required 10^{-5}

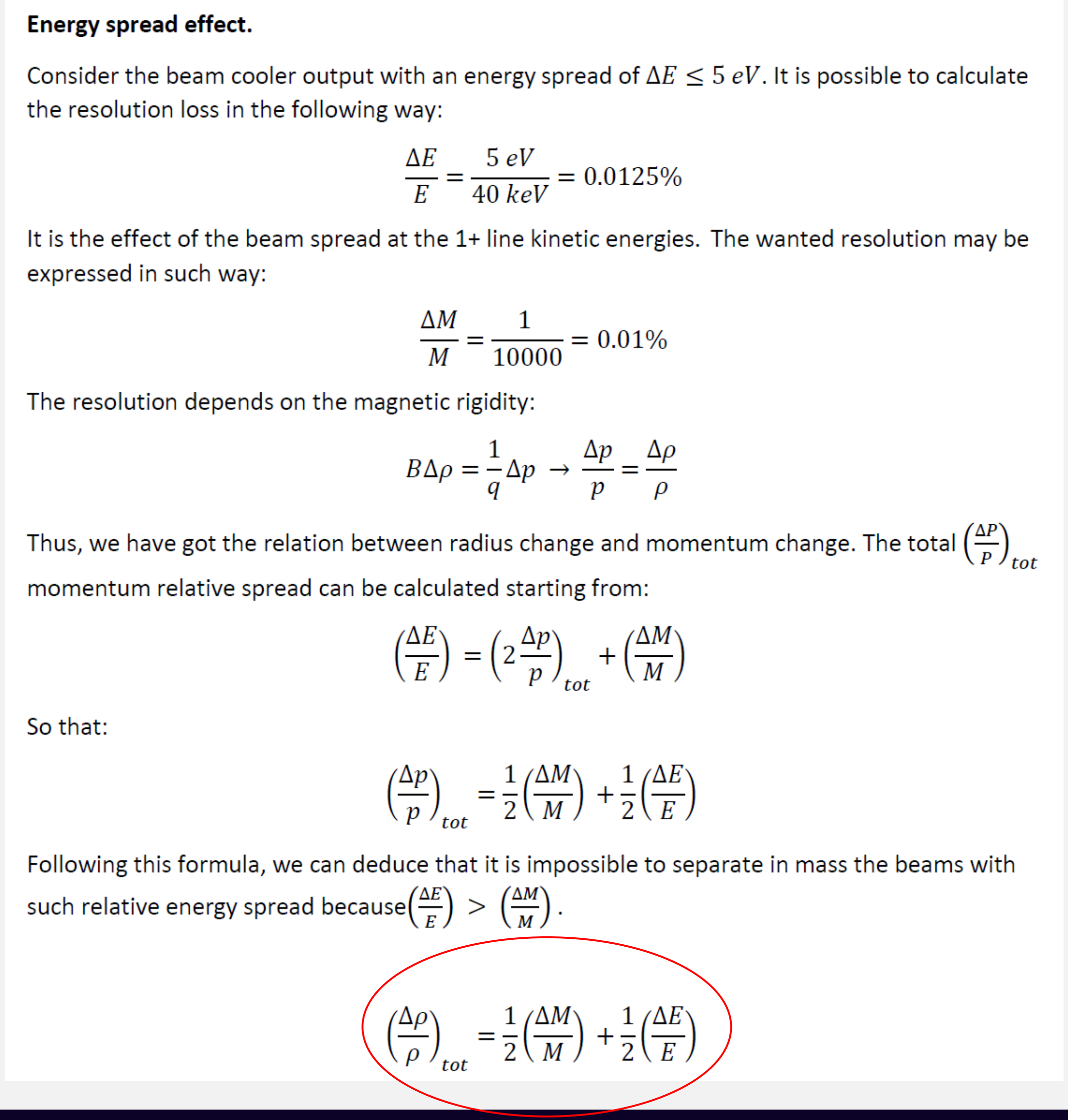
Dipole homogeneity and
Power supply stability
Required 10^{-5}

Geometrical precision and stability (vibration)
Required 10^{-5}

Resolution with energy spread
Required $5\ 10^{-5}$

*from $\frac{\Delta m}{m}-\frac{\Delta w}{w}=2\frac{\Delta B\rho}{B\rho}$

Beam Energy spread effect on resolution



Energy spread effect.

Consider the beam cooler output with an energy spread of $\Delta E \leq 5\ eV$. It is possible to calculate the resolution loss in the following way:

$$\frac{\Delta E}{E} = \frac{5\ eV}{40\ keV} = 0.0125\%$$

It is the effect of the beam spread at the 1+ line kinetic energies. The wanted resolution may be expressed in such way:

$$\frac{\Delta M}{M} = \frac{1}{10000} = 0.01\%$$

The resolution depends on the magnetic rigidity:

$$B\Delta\rho = \frac{1}{q}\Delta p \rightarrow \frac{\Delta p}{p} = \frac{\Delta\rho}{\rho}$$

Thus, we have got the relation between radius change and momentum change. The total $\left(\frac{\Delta P}{P}\right)_{tot}$ momentum relative spread can be calculated starting from:

$$\left(\frac{\Delta E}{E}\right) = \left(2\frac{\Delta p}{p}\right)_{tot} + \left(\frac{\Delta M}{M}\right)$$

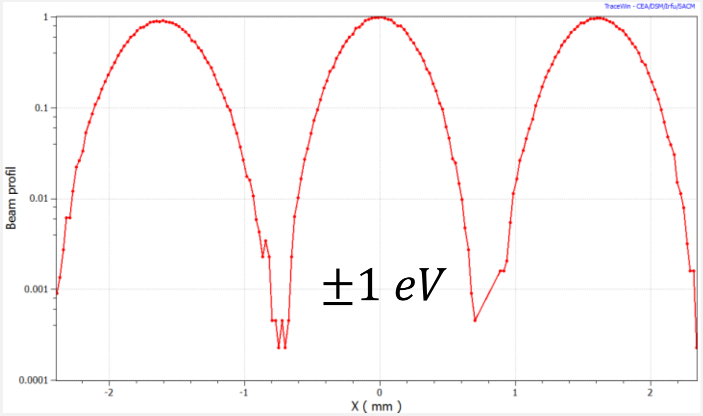
So that:

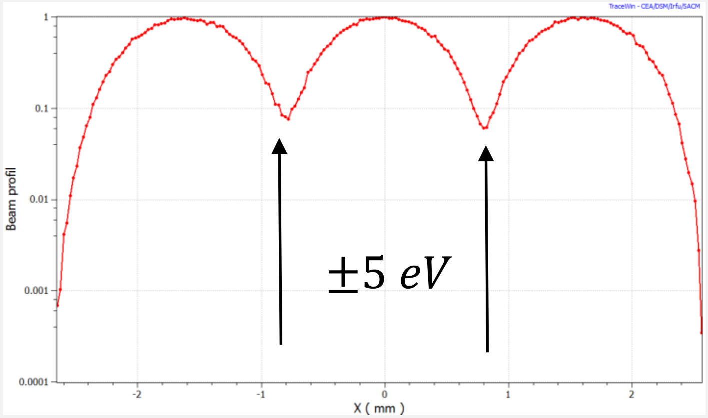
$$\left(\frac{\Delta p}{p}\right)_{tot} = \frac{1}{2}\left(\frac{\Delta M}{M}\right) + \frac{1}{2}\left(\frac{\Delta E}{E}\right)$$

Following this formula, we can deduce that it is impossible to separate in mass the beams with such relative energy spread because $\left(\frac{\Delta E}{E}\right) > \left(\frac{\Delta M}{M}\right)$.

$$\left(\frac{\Delta\rho}{\rho}\right)_{tot} = \frac{1}{2}\left(\frac{\Delta M}{M}\right) + \frac{1}{2}\left(\frac{\Delta E}{E}\right)$$

Different resolutions @ the image point for 3 1/20000 separated in mass beams, due to the larger energy spread.





Why the spectrometer on HV platform?

- Increasing the energy of the beam reduces the effect of the energy spread term and shrinks the geometric emittance (x’ component). This means an easier transport through the separator dipoles.
- The energy spread set a theoretical limit for the maximum resolution. For the case of the HRMS we get:

$$\frac{\Delta \mathrm{E}}{\mathrm{E}} = \frac{1\ \mathrm{eV}}{160\ \mathrm{keV}} = \frac{1}{160000}$$

$$\frac{\Delta \mathrm{E}}{\mathrm{E}} = \frac{1\ \mathrm{eV}}{40\ \mathrm{keV}} = \frac{1}{40000}$$

without HV platform

- The situation worsen immediately: if we have 5 eV, 20 eV of energy spread we get:

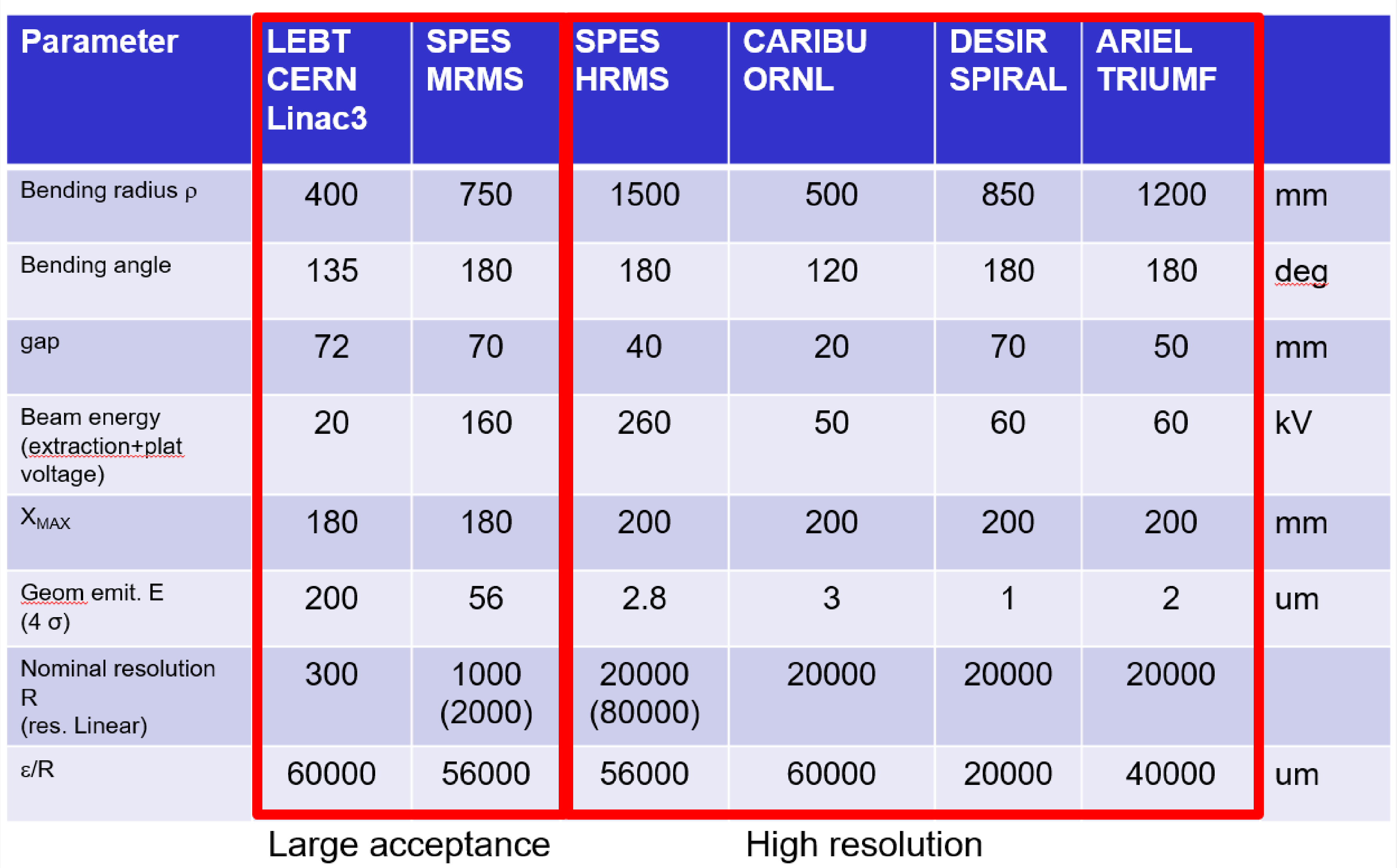
$$\frac{\Delta \mathrm{E}}{\mathrm{E}} = \frac{5\ \mathrm{eV}}{160\ \mathrm{keV}} = \frac{1}{32000}$$

$$\frac{\Delta m}{m} \propto 2\frac{\Delta E}{E}$$

$$\frac{\Delta \mathrm{E}}{\mathrm{E}} = \frac{20\ \mathrm{eV}}{160\ \mathrm{keV}} = \frac{1}{8000}$$

without Beam Cooler

Main parameters of Spectrometers

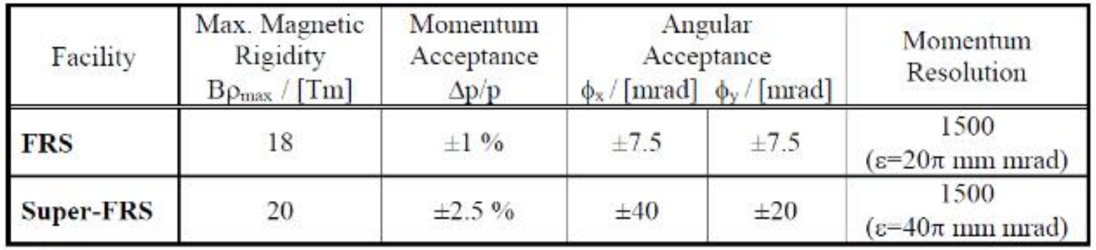


Parameter	LEBT CERN Linac3	SPES MRMS	SPES HRMS	CARIBU ORNL	DESIR SPIRAL	ARIEL TRIUMF	
Bending radius ρ	400	750	1500	500	850	1200	mm
Bending angle	135	180	180	120	180	180	deg
gap	72	70	40	20	70	50	mm
Beam energy (extraction+plat voltage)	20	160	260	50	60	60	kV
X_{MAX}	180	180	200	200	200	200	mm
Geom emit. E (4 σ)	200	56	2.8	3	1	2	um
Nominal resolution R (res. Linear)	300	1000 (2000)	20000 (80000)	20000	20000	20000	
ε/R	60000	56000	56000	60000	20000	40000	um

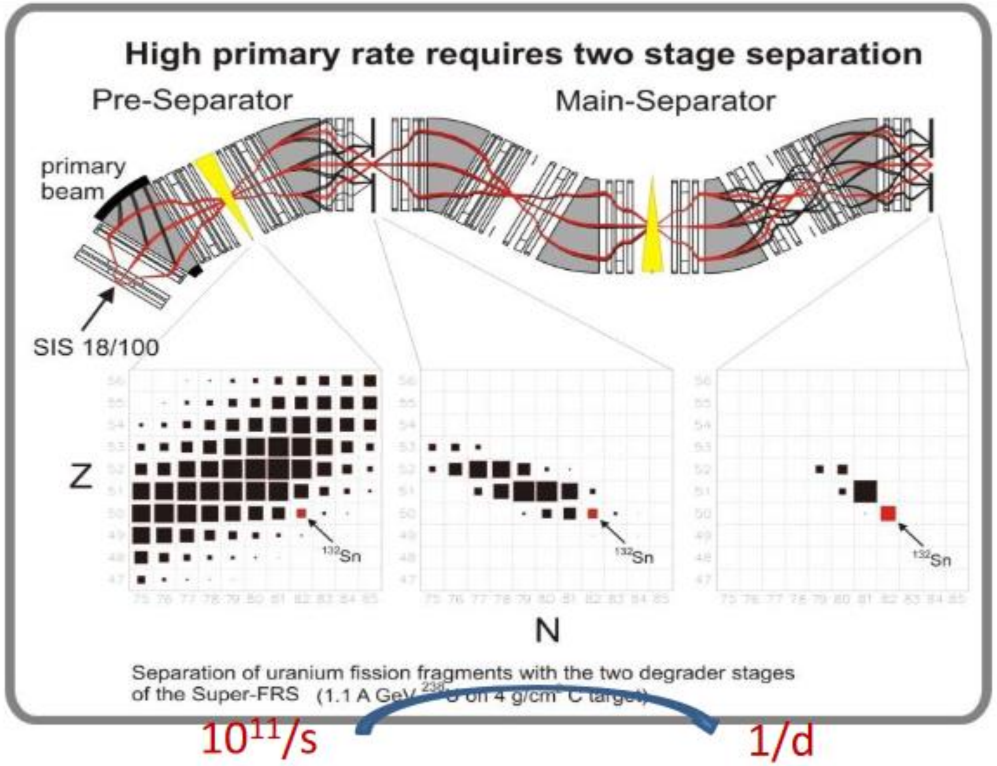
Large acceptance

High resolution

Fragment Separator (HIGH Energy) S+U shape



Facility	Max. Magnetic Rigidity $B\rho_{max}$ / [Tm]	Momentum Acceptance $\Delta p/p$	Angular Acceptance ϕ_x / [mrad]	ϕ_y / [mrad]	Momentum Resolution
FRS	18	±1 %	±7.5	±7.5	1500 (ε=20π mm mrad)
Super-FRS	20	±2.5 %	±40	±20	1500 (ε=40π mm mrad)



Separation of uranium fission fragments with the two degrader stages of the Super-FRS (1.1 A GeV ^{238}U on 4 g/cm^2 C target)

High projectile energy and multiple separator stages to efficiently reduce the background from contaminations

ARIS

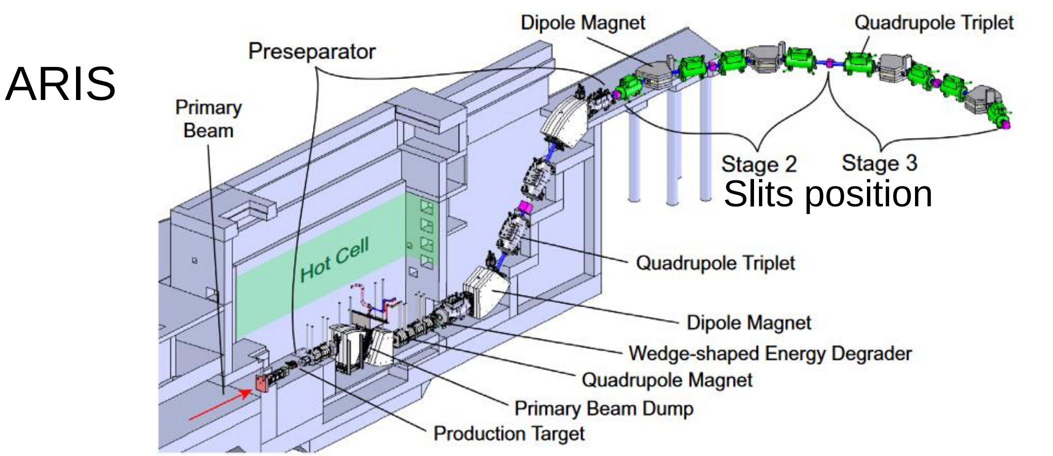


Fig. 1. Overview of the design of the Advanced Rare Isotope Separator (ARIS) at FRIB. The primary beam from the driver linac reaches the production target from the bottom left in the figure, as indicated by a red arrow. The first part of the preseparator is located inside of a hot cell that is part of the production target facility. The extent of the hot cell is indicated schematically. A beam dump system between the first two dipole magnets intercepts the primary beam. The rare isotope beam is then guided to the above-grade second and third stages of ARIS, from where it is sent to experiments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

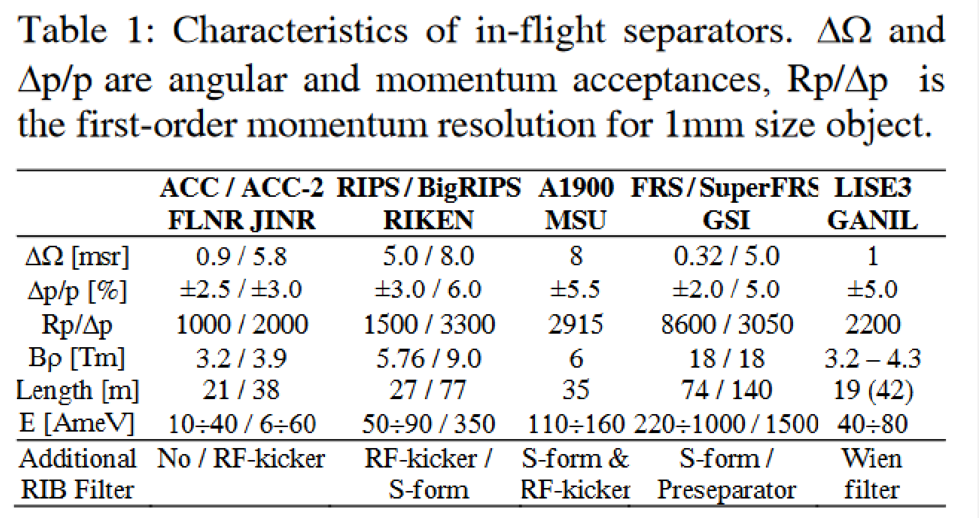


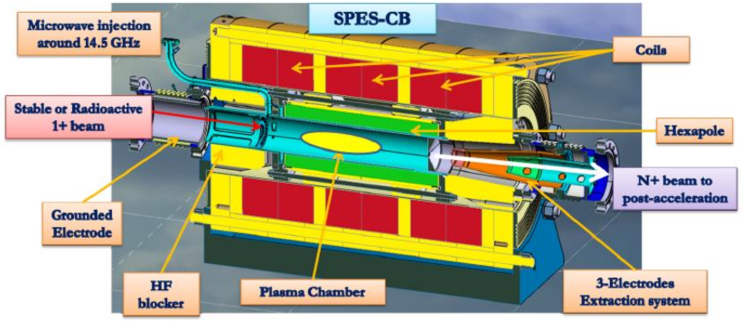
Table 1: Characteristics of in-flight separators. $\Delta\Omega$ and $\Delta p/p$ are angular and momentum acceptances, $Rp/\Delta p$ is the first-order momentum resolution for 1mm size object.

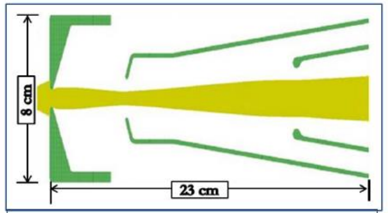
	ACC / ACC-2 **FLNR JINR**	**RIPS / BigRIPS** **RIKEN**	**A1900** **MSU**	**FRS / SuperFRS** **GSI**	**LISE3** **GANIL**
$\Delta\Omega$ [msr]	0.9 / 5.8	5.0 / 8.0	8	0.32 / 5.0	1
$\Delta p/p$ [%]	±2.5 / ±3.0	±3.0 / 6.0	±5.5	±2.0 / 5.0	±5.0
$Rp/\Delta p$	1000 / 2000	1500 / 3300	2915	8600 / 3050	2200
$B\rho$ [Tm]	3.2 / 3.9	5.76 / 9.0	6	18 / 18	3.2 – 4.3
Length [m]	21 / 38	27 / 77	35	74 / 140	19 (42)
E [AmeV]	10÷40 / 6÷60	50÷90 / 350	110÷160	220÷1000 / 1500	40÷80
Additional RIB Filter	No / RF-kicker	RF-kicker / S-form	S-form & RF-kicker	S-form / Preseparator	Wien filter

CHARGE BREEDER: from 1+ to N+ beam

SPES ECRIS

- 2^{nd} generation ECR source
- 3 coils for axial magnetic field (1.2 T at the injection, 0.42 T minimum and 0.82 T at extraction). 14.5 GHz microwave with a maximum power of 600 W
- Three electrode extraction system: from 40 kV to 20 kV depending on the a/q ratio.
- $\varepsilon_{rms,n} = 0.0486\ mm\ mrad$ **measured during the test bench @LPSC in March 2015 [1]**





Kobra 3D simulations benchmarked by the test bench within 10%. [1]

Mass Range			ION	Q	Efficiency [%]	Year Data Source	(M/q)_min	(M/q)_max
		138	Xe	20+ (21+)	10,9 (6,2)	2012 (2005)	6.57	6.90
130	132	134	Sn	21+	6	2005	6.19	6.38
		98	Sr	14+	3.5	2005	7	7
		94	Kr	16+(18+)	12(8,5)	2013	5.22	5.88
90	………..	99	Y	14+	3.3	2002	6.43	7.07
74	………..	80	Zn	10+	2.8	2002	7.40	8.00
	81	82	Ga	11+	2	2002	7.36	7.45
90	91	92	Rb	17+	7.50	2013	5.29	5.41
		34	Ar	8+(9+)	16,2(11,5)	2012 (2013)	3.78	4.25

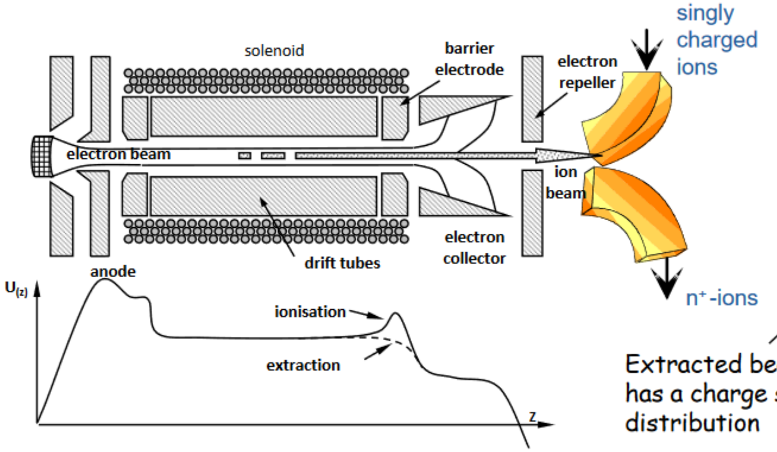
[1] The SPES-Charge Breeder (SPES CB) and its beam line INFN-LNL, Alessio Galatà et Al. EMIS15

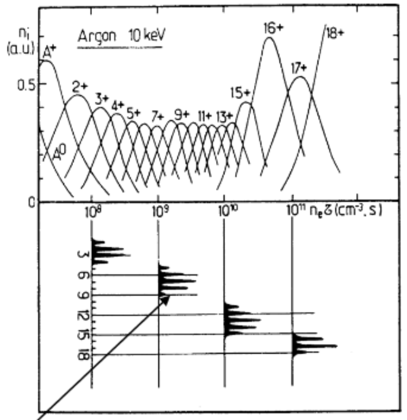
	TRAP/EBIS	ECRIS
* EFFICIENCY: (IN ONE CHARGE STATE)	5-10% (INCLUDING TRAP)	5-10% CW EXTRACTION 2-5% AFTERGLOW
* ENERGY SPREAD:	<50 EV*Q	FEW EV
* MAXIMUM THROUGHPUT:	1E9 IONS/S	1E12 IONS/S
* LOWER CURRENT LIMIT:	FA	10 NA
* BREEDING TIME:	A/Q < 4 IN 20 MS FOR A = 50 IN 160 MS FOR A = 150	A/Q < 6 IN 50 MS FOR A = 50
* STORAGE CAPACITY:	1E11 CHARGES/PULSE (PENNING TRAP LIMIT 1E7 CHARGES/PULSE)	>2E12 CHARGES/PULSE
* STORAGE TIME:	FEW SECONDS	< 100 MS?
* INJECTION:	PULSED - A FEW 10 µS	CW OR PULSED
* EXTRACTION:	PULSED - 10-50 µS	CW OR AFTERGLOW <MS

ISOLDE

EBIS basics

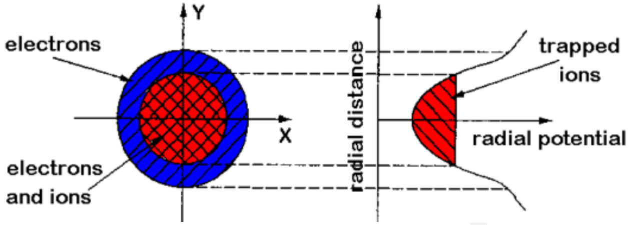
Electron beam ion source



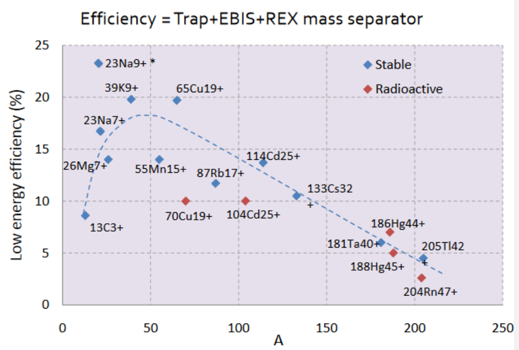


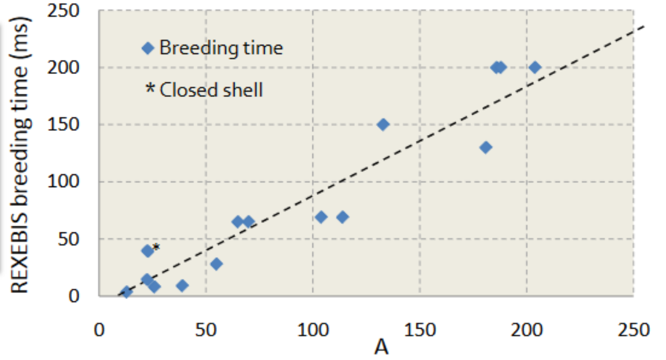
Charge development for stepwise ionisation

Extracted beam has a charge state distribution



- * Produces multiply charged ions
- * Ions are trapped in a magneto-electrostatic trap
- * Ionisation by e⁻ bombardment from an mono-energetic e⁻ beam

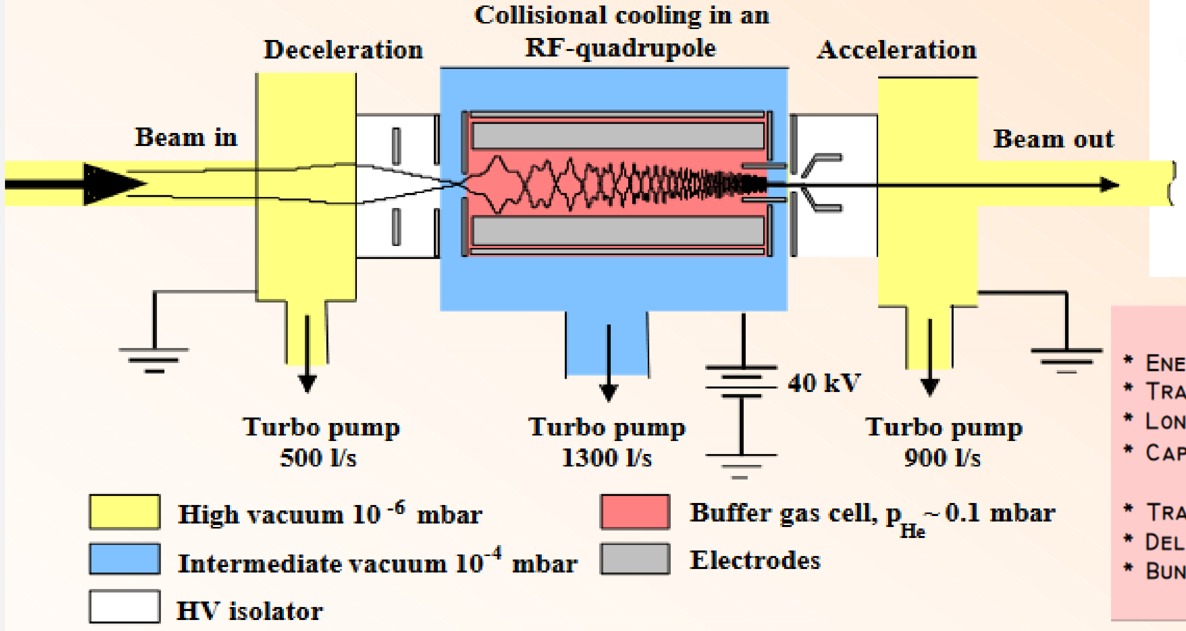


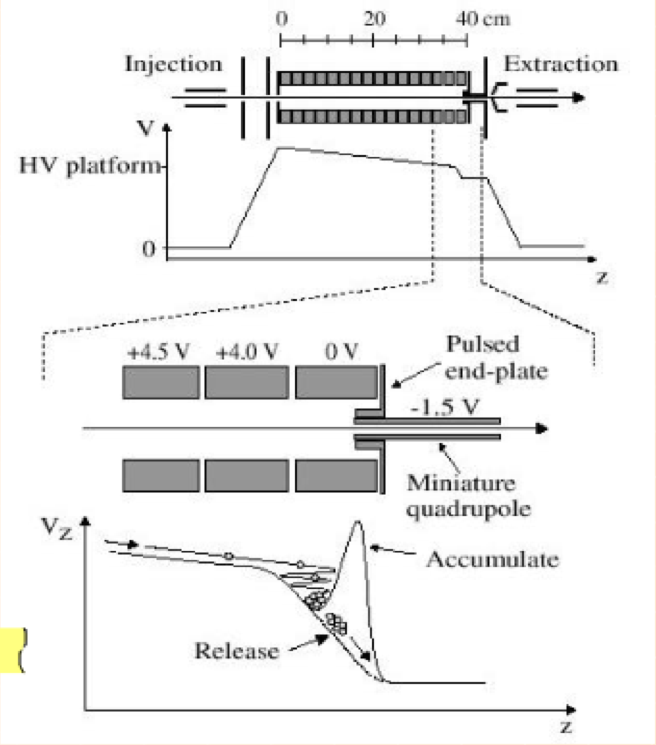


RFQ BEAM COOLER: reduce the emittance and energy spread

Benefits

- * Higher beam transport efficiency
- * Higher resolution in mass separator
- * Improved sensitivity of any precision spectroscopy (e.g. laser spectroscopy)
- * Effective injection in to charge breeders and traps
- * Beam bunching -> increased noise-to-signal ratio



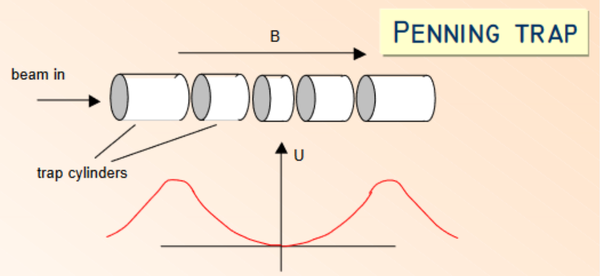


Data

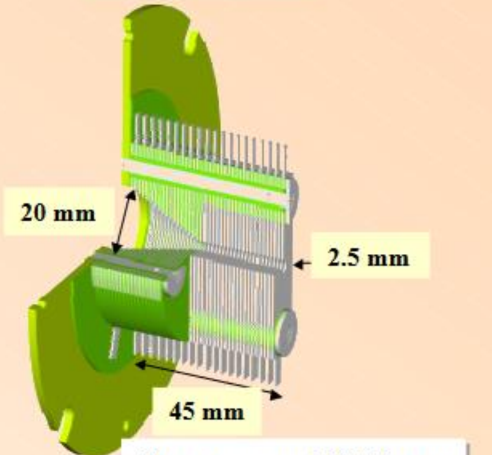
- * Energy spread < 1 eV (from ~100 eV)
- * Transverse emittance – a few π mm mrad (40 keV)
- * Longitudinal emittance < 10 µs*eV
- * Capacity bunched mode - 1E3-1E5 ions
  DC - 10 nA
- * Transmission efficiency - ~50% (DC and bunched mode)
- * Delay time (with axial field) ~1 ms
- * Bunching Accumulation time 10 ms to 1 s
  Bunch width 5-20 µs (FWHM)

Other type of beam cooler

Penning trap



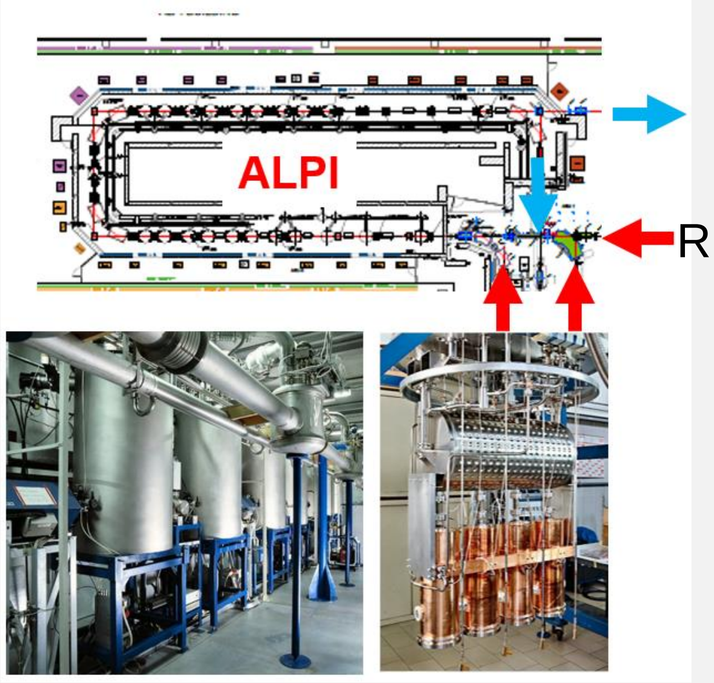
RF-funnel



Worked on at LMU Munich
High current capability

POST ACCELERATOR

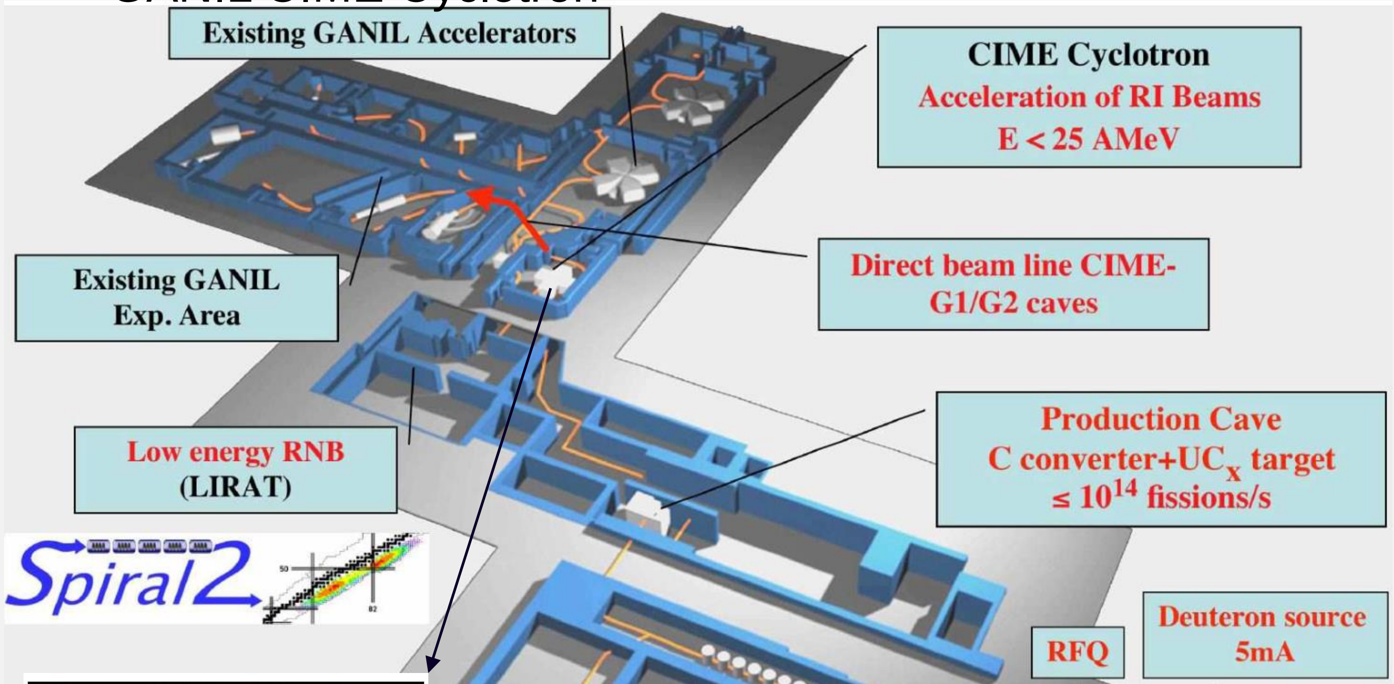
SPES SC LINAC



RiBs input

- Folded independent cavity linac
- Design and built 80’-90’
- One of the first prototypes in Europe.
- 77 QWs cavities at 4 K
  - 80 MHz low beta (0.045)
  - 160 MHz medium beta (0.1)
  - 160 MHz high beta (0.12)
- Low energy ions of about 10 MeV/amu

GANIL CIME Cyclotron



RiBs efficiency

$$I = \Phi \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_3 \cdot \varepsilon_4 \cdot \varepsilon_5 \cdot \varepsilon_6 \cdot \varepsilon_7$$

$I \rightarrow$ rib beam intensity

$\Phi \rightarrow$ rib production as particles/s

$\varepsilon_1 \rightarrow$ product release (≈ 0.9)

$\varepsilon_2 \rightarrow$ ion source efficiency (≈ 0.3)

$\varepsilon_3 \rightarrow$ efficiency of rib decay (≈ 0.95)

$\varepsilon_4 \rightarrow$ efficiency of beam cooler (≈ 0.5)

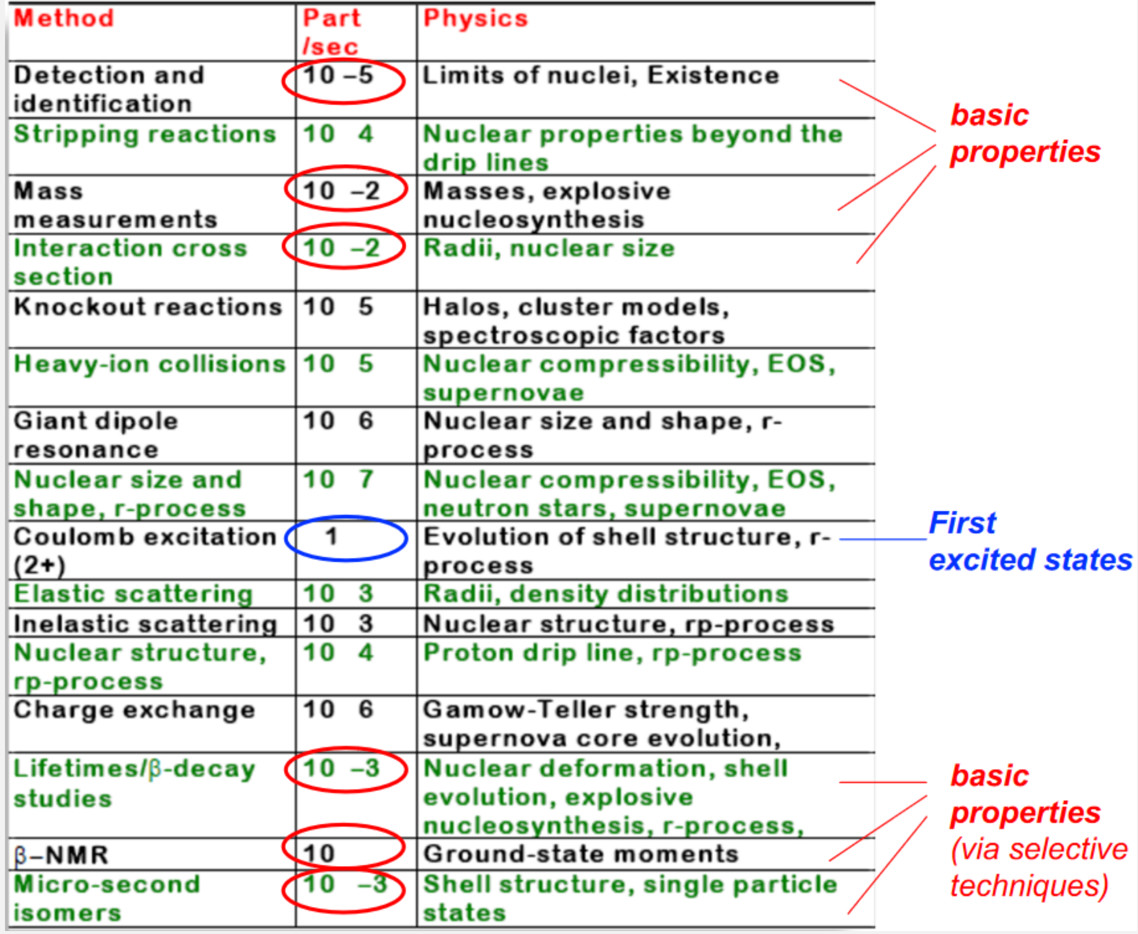
$\varepsilon_5 \rightarrow$ efficiency of charge breeder (≈ 0.2)

$\varepsilon_6 \rightarrow$ efficiency of spectrometer (≈ 0.9)

$\varepsilon_7 \rightarrow$ efficiency of post accelerator (≈ 0.5)

With 10^8 pps rib production we fast get below 10^6 pps post-accelerated at the experiment

Minimum useful intensity for RiBs at experiment



Method	Part /sec	Physics
Detection and identification	10 –5	Limits of nuclei, Existence
Stripping reactions	10 4	Nuclear properties beyond the drip lines
Mass measurements	10 –2	Masses, explosive nucleosynthesis
Interaction cross section	10 –2	Radii, nuclear size
Knockout reactions	10 5	Halos, cluster models, spectroscopic factors
Heavy-ion collisions	10 5	Nuclear compressibility, EOS, supernovae
Giant dipole resonance	10 6	Nuclear size and shape, r-process
Nuclear size and shape, r-process	10 7	Nuclear compressibility, EOS, neutron stars, supernovae
Coulomb excitation (2+)	1	Evolution of shell structure, r-process
Elastic scattering	10 3	Radii, density distributions
Inelastic scattering	10 3	Nuclear structure, rp-process
Nuclear structure, rp-process	10 4	Proton drip line, rp-process
Charge exchange	10 6	Gamow-Teller strength, supernova core evolution,
Lifetimes/β-decay studies	10 –3	Nuclear deformation, shell evolution, explosive nucleosynthesis, r-process,
β–NMR	10	Ground-state moments
Micro-second isomers	10 –3	Shell structure, single particle states

basic properties

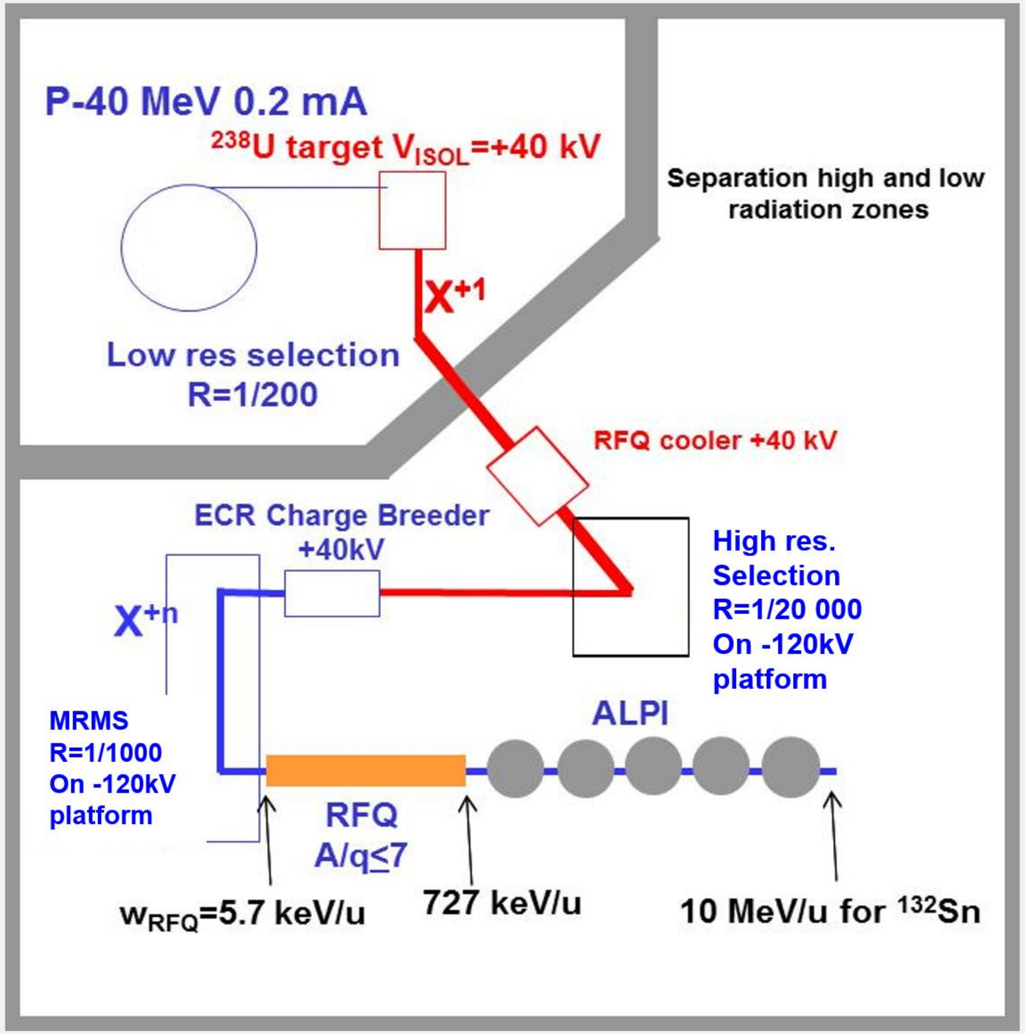
First excited states

basic properties *(via selective techniques)*

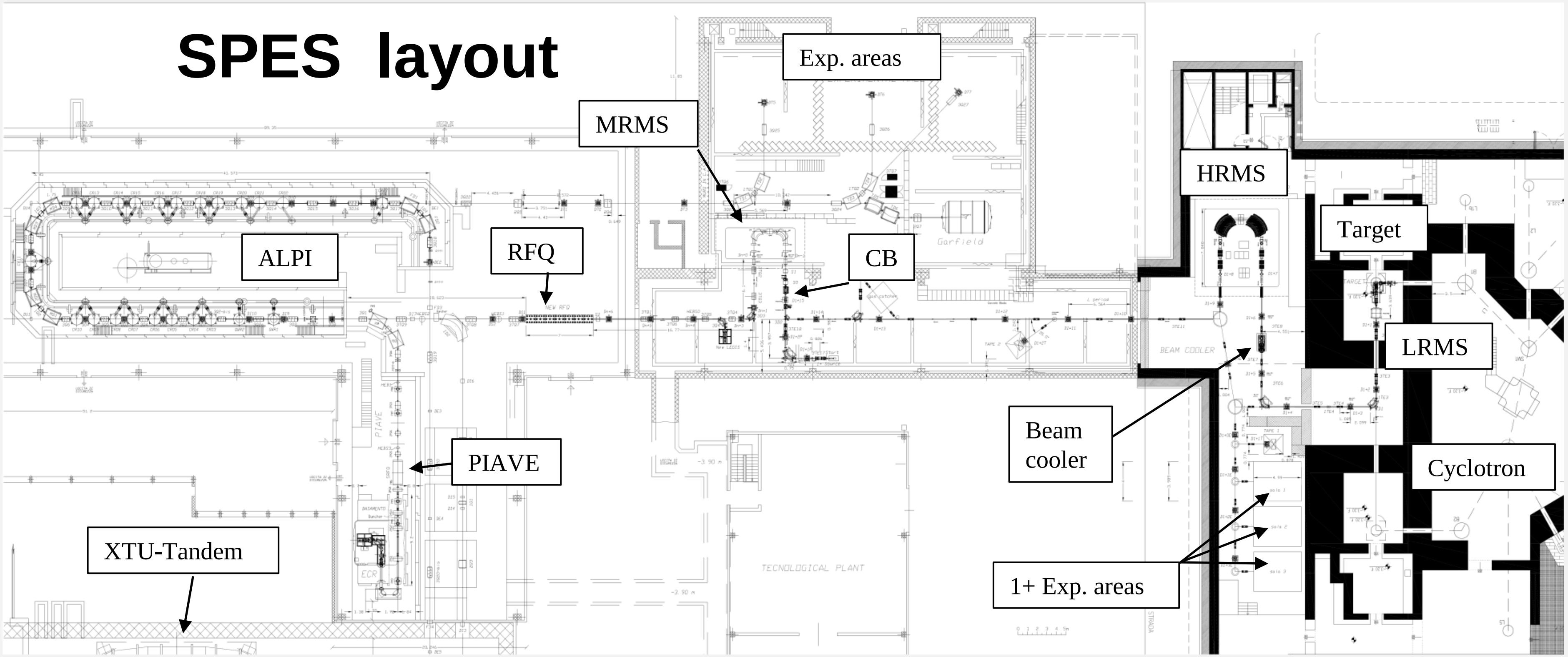
6.25*10^9 pps = 1 pnA

Whole Beam Optics Design of SPES

- The SPES cyclotron as primary driver.
- The target .
- The high-resolution stage: RFQ Cooler and the HRMS.
- The transfer lines to the Low energy Experimental areas and to the Charge Breeder.
- The post acceleration stage: charge breeder and the MRMS with the purity issue.
- The matching line from CB to the SPES RFQ injector for ALPI LINAC
- ALPI LINAC as post-accelerator with Rare Beams.



SPES layout



- The SPES facility may be divided in three stages: the RIB production, the magnetic isotope separation and the charge breeding with the post-accelartion.
- Low current beams (nA-fA) and transfer line with high dispersion require a careful manage of the beam optics.
- Several localised separation stages are needed for separate the nominal beam from the isotopes and fit the safety requirements.
- Very long transfer lines are needed in order to fit the new building with the existing linac ALPI.

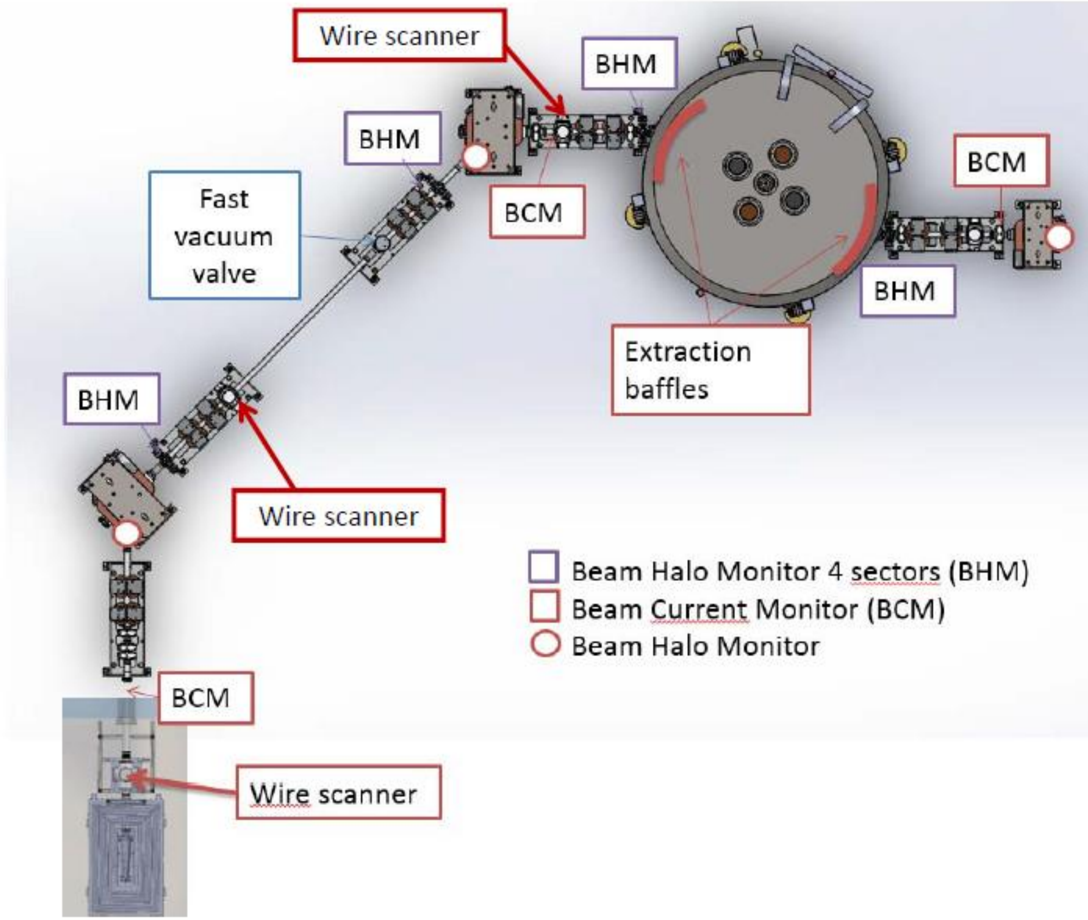
- The **cyclotron** accelerates 70 MeV proton beam of 750 μA onto a UCx **target**, heated at 2000 C°. The radioactive ions produced are extracted @ 20-40 keV, depending on the RFQ's β_s of the n+ beams.
- There are three separation stages: the **LRMS**, composed by a Wien filter and a 90° magnetic dipole 1/200 resolution in mass (isobar selection); the **HRMS**, with a capability of 1/20000 resolution (isotope separation) in mass and the **MRMS** of 1/1000, which removes the CB contaminants.
- The beam gains 1+ -> n+ charge and, after the removal of the **CB** contaminants is sent to an internal bunching **RFQ**, which accelerates the beam up to 727.3 keV/A (for A/q=7).
- The beam is longitudinally matched with the linac via a **MEBT** line (with two bunchers). The **ALPI linac** accelerates the beam up to 10 MeV/A .
- There are two experimental areas: the 1+ experimental areas down to the HRMS complex and the experimental areas down to ALPI for the post accelerated beams.

Cyclotron

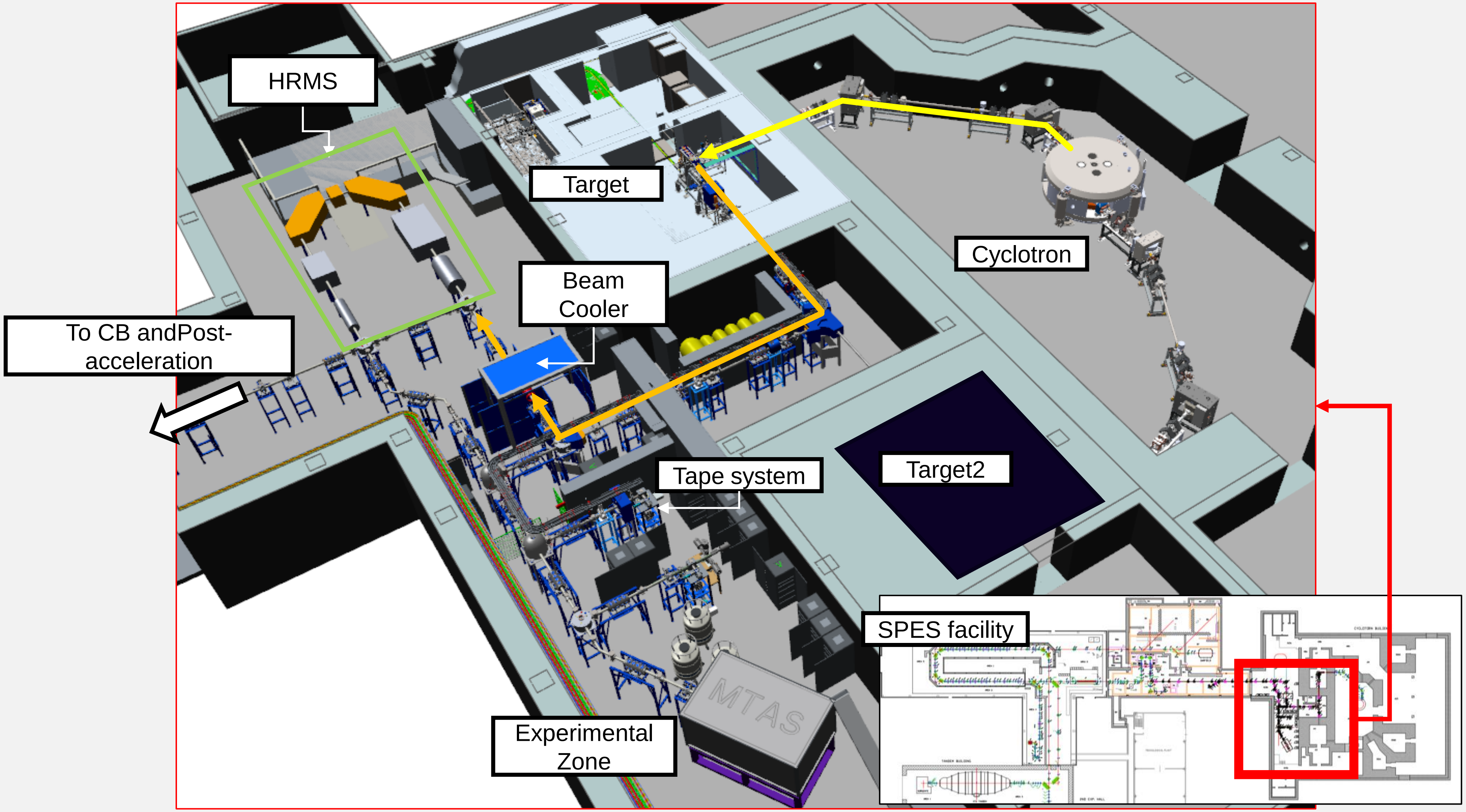
Beam transport at high current (35 kW beam power)

- To get **500 µA** on target
- Ion Source setting at **8.5mA**
- Injection acceptance ~11% (40 RF deg)
- optimize acceleration RF phase → ~40% current lost in CR
- Acceleration efficiency >95%
- Extraction efficiency >99%
- Transport efficiency >99%

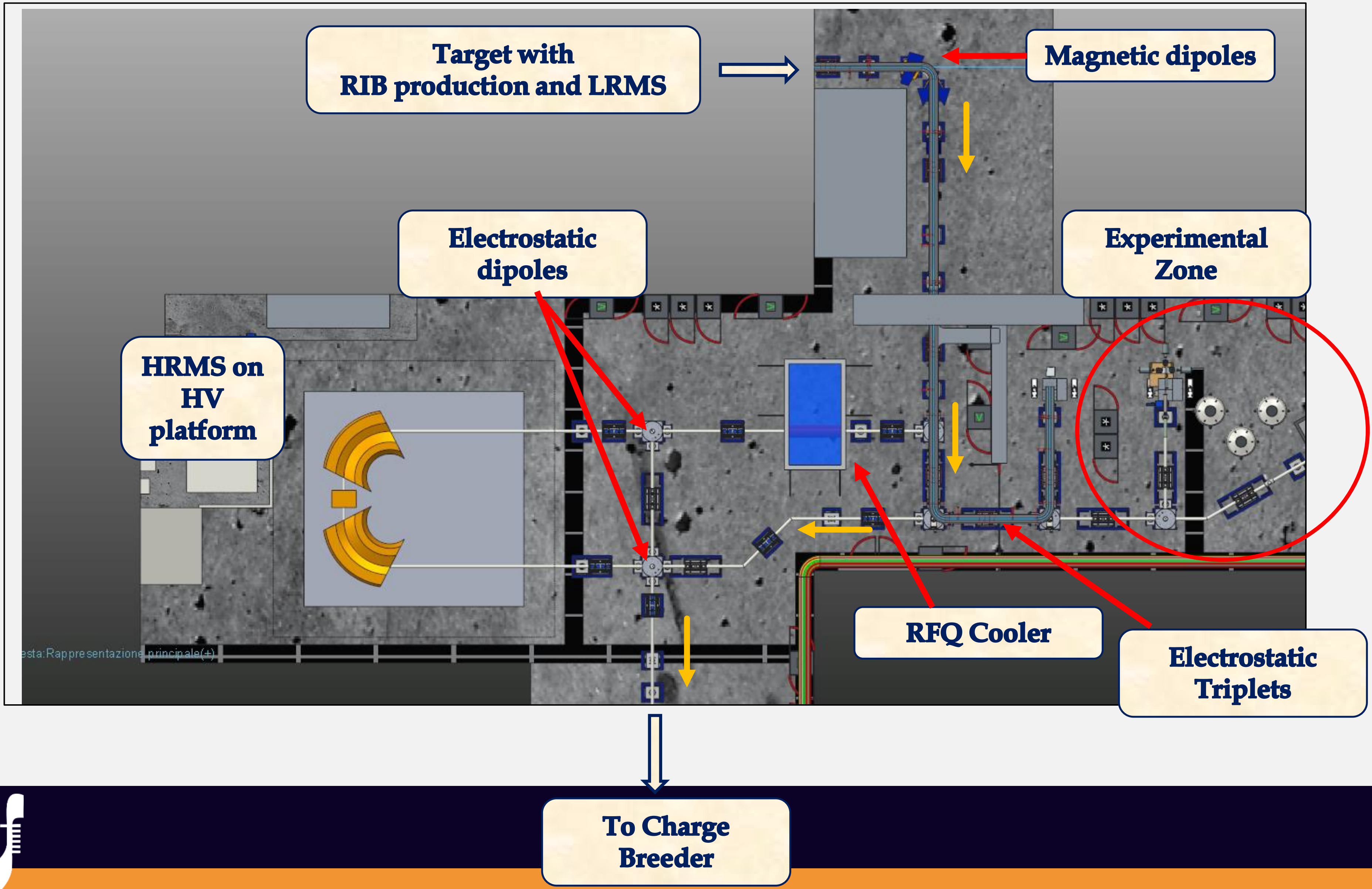
I_{target} / I_{IS} ~ 6%



From cyclotron to HRMS



Beam Transport Line from Target to Charge Breeder



Target with
RIB production and LRMS

Magnetic dipoles

Electrostatic
dipoles

Experimental
Zone

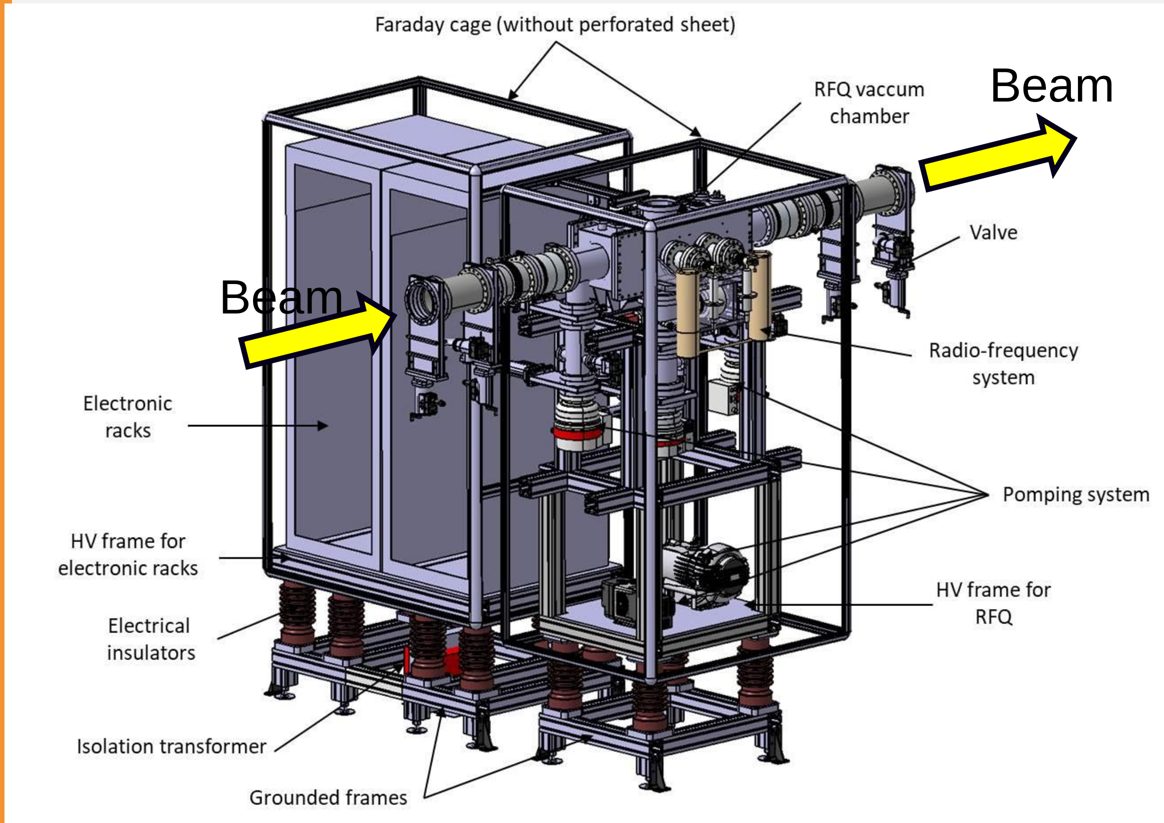
HRMS on
HV
platform

RFQ Cooler

Electrostatic
Triplets

To Charge
Breeder

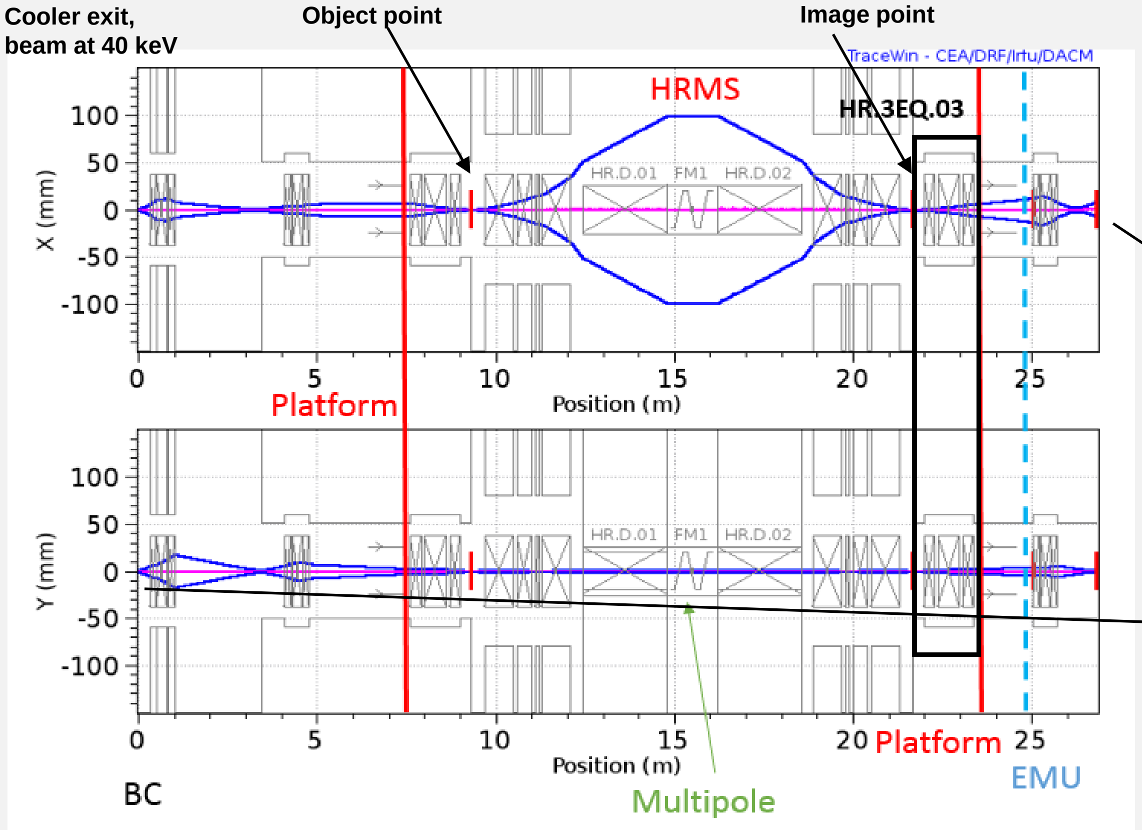
SPES RFQ Cooler

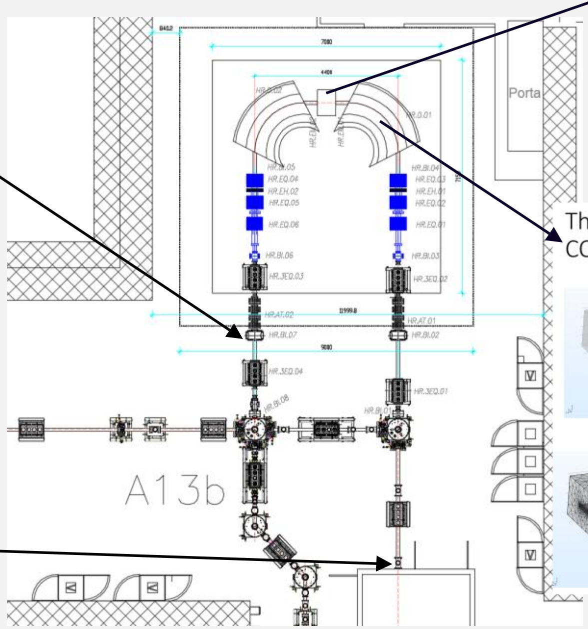


Parameters	Requested values
Transmission	>80%
Output beam Transverse Emittance (RMS norm)	< 1.5 E-3 pi.mm.mrad
Output Beam Energy Spread (FWHM)	< 0.7 eV
Input Beam maximum/nominal Current	100 nA / 50 nA
Energy of Beams at RFQC Output (*)	$V_{platform}$
Reduction factor of emittance $\varepsilon_{in}/\varepsilon_{out}$	>10

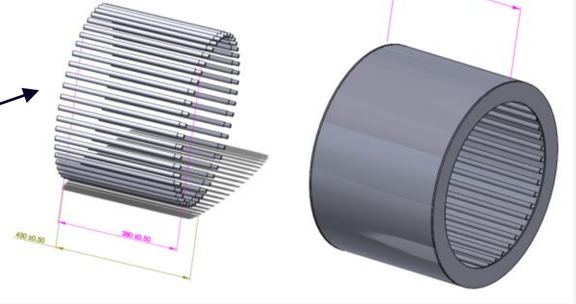
Element	Mass	Beam Current	Transmission	Energy spread FWHM	RMS Emittance @ 5keV	RMS normalised Emittance
Lithium	7 uma	**50 nA**	61%	0,82 eV	7,79 pi.mm.mrad	9,64 E-3 pi.mm.mrad
Potassium	39 uma	**50 nA**	70%	0,9 eV	5,37 pi.mm.mrad	2,82 E-3 pi.mm.mrad
Potassium	39 uma	**100 nA**	82%	1,05 eV	7,25 pi,mm.mrad	3,80 E-3 pi.mm.mrad
Cesium	133 uma	**50 nA**	63%	1,15 eV	7,25 pi.mm.mrad	2,06 E-3 pi.mm.mrad
Cesium	133 uma	**100 nA**	67%	1 eV	7,78 pi.mm.mrad	2,21 E-3 pi.mm.mrad

HRMS Multiparticle Beam envelope

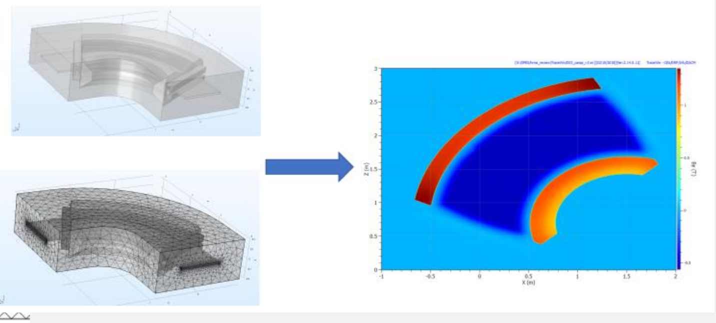




48 electrodes multipole

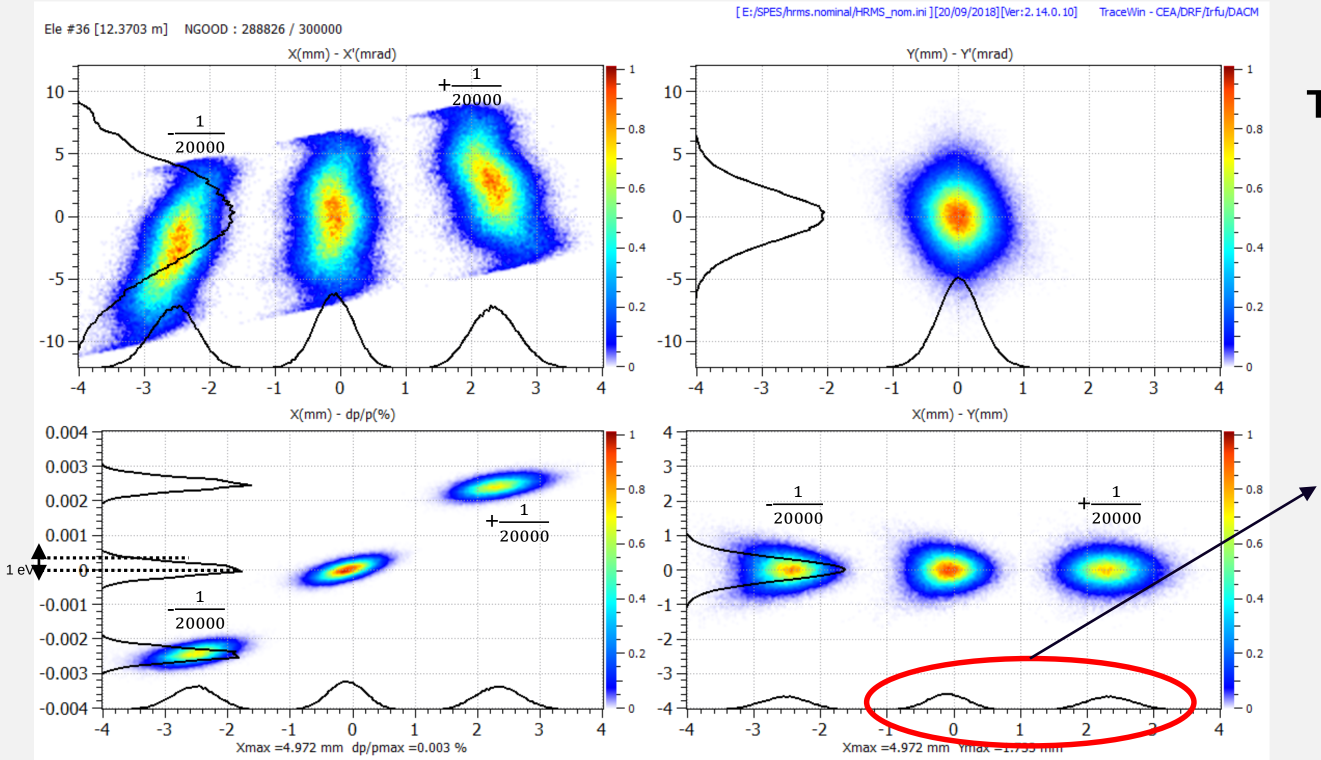


The dipole has been designed with OPERA and re-calculated with COMSOL. The generated 3D fields are imported inside TraceWin.

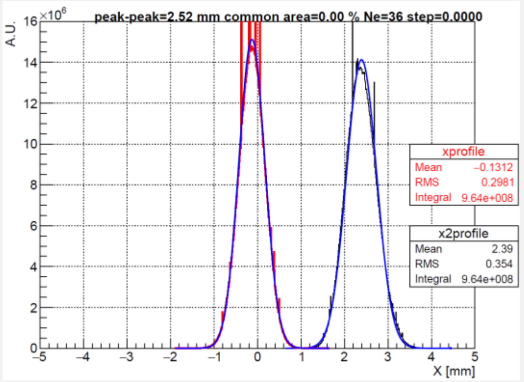


The beam dynamics from the RFQ Cooler through the HRMS to the EMU device is show.

HRMS Beam Separation without slits at image point with a gaussian beam (cut at 4σ) and 1eV (rms) as energy spread

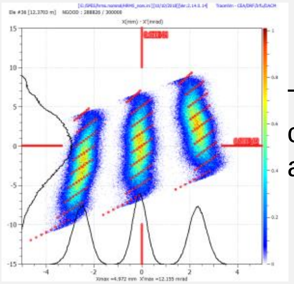


Total beam size=2 mm

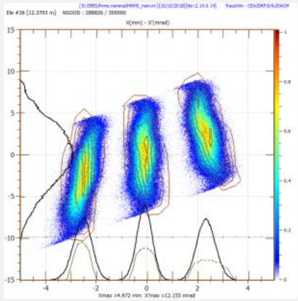


2.5 mm Beam separation

The output of TraceWin has been
post-proceed with ROOT to calculate
the beams separation and the common area

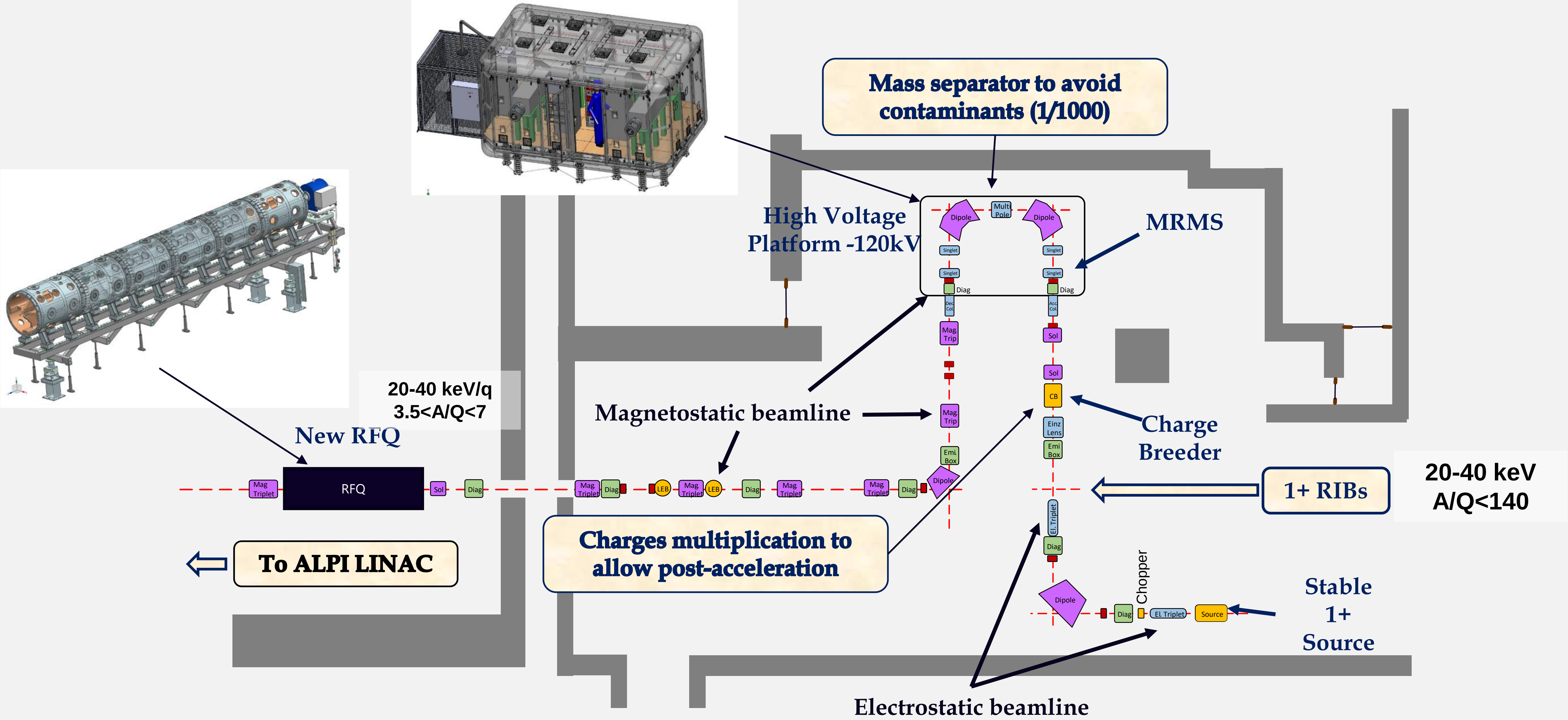


The output of **TraceWin** has been compared with **COSY 5° order** (red dots) and the results are the same.



The output of **TraceWin** has been compared with **GIOS 3° order** (Brown lines) and the results are the same.

From the 1+ transport line to RFQ



Mass separator to avoid contaminants (1/1000)

High Voltage Platform -120kV

MRMS

20-40 keV/q
3.5<A/Q<7

New RFQ

Magnetostatic beamline

Charge Breeder

1+ RIBs

20-40 keV
A/Q<140

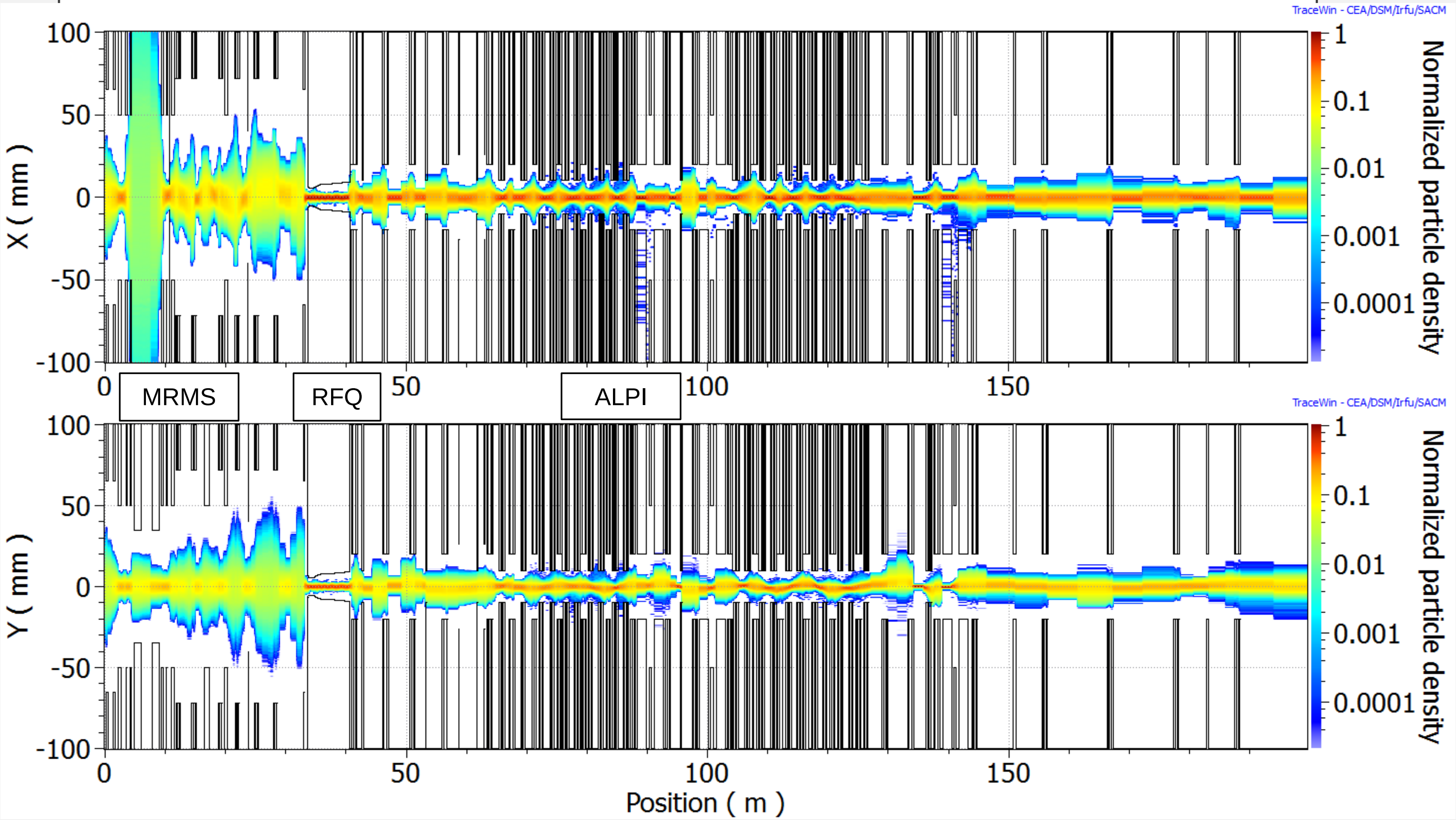
To ALPI LINAC

Charges multiplication to allow post-acceleration

Stable 1+ Source

Electrostatic beamline

End to end simulation from the CB to end of ALPI

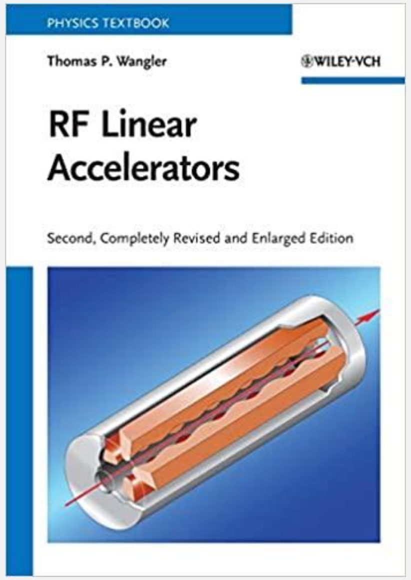


L. Bellan, “New techniques for the LNL superconductive Linac ALPI beam dynamics simulations and commissioning” **TUODA3**

- Case of ${}^{132}Sn^{19+}$ @ 0.76 MeV with 0.1 mm mrad from the CB and +-15 eV of energy spread.
- The total losses in the nominal case are less than 14%, the final energy is 1200 MeV

References

- https://www.dacm-logiciels.fr/ (TraceWin Beam Dynamic Code)
- https://www.jacow.org/Main/Proceedings (Conference Proceedings)
- https://uspas.fnal.gov/materials/materials-table.shtml (Particle Accelerator School)



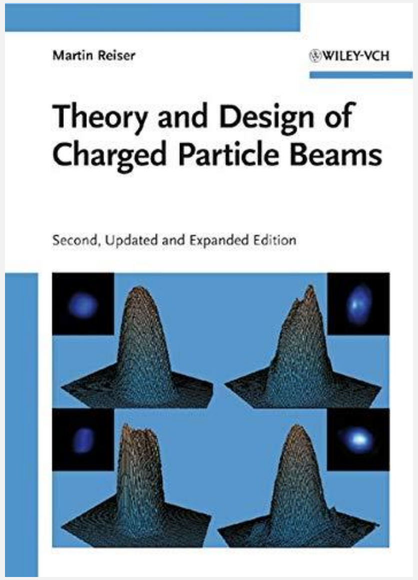
PHYSICS TEXTBOOK

Thomas P. Wangler

WILEY-VCH

RF Linear Accelerators

Second, Completely Revised and Enlarged Edition

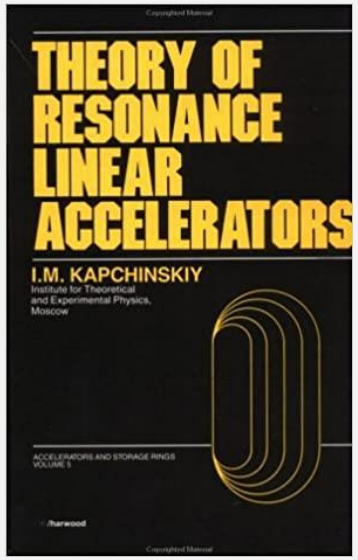


Martin Reiser

WILEY-VCH

Theory and Design of Charged Particle Beams

Second, Updated and Expanded Edition



THEORY OF RESONANCE LINEAR ACCELERATORS

I.M. KAPCHINSKIY

Institute for Theoretical
and Experimental Physics,
Moscow

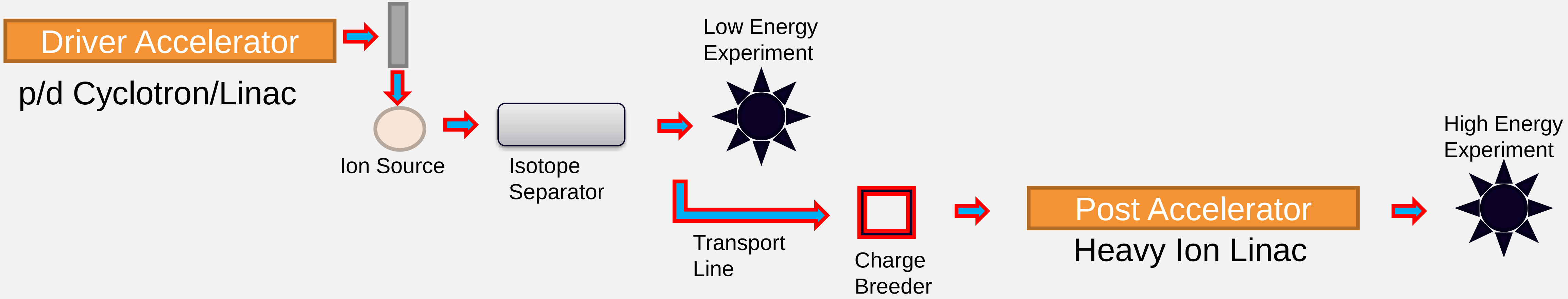
ACCELERATORS AND STORAGE RINGS
VOLUME 5

harwood

How to generate RiBs

ISOL

Isotope Separation On-Line



Driver Accelerator

p/d Cyclotron/Linac

Thick and hot
Production target

Ion Source

Isotope
Separator

Low Energy
Experiment

Transport
Line

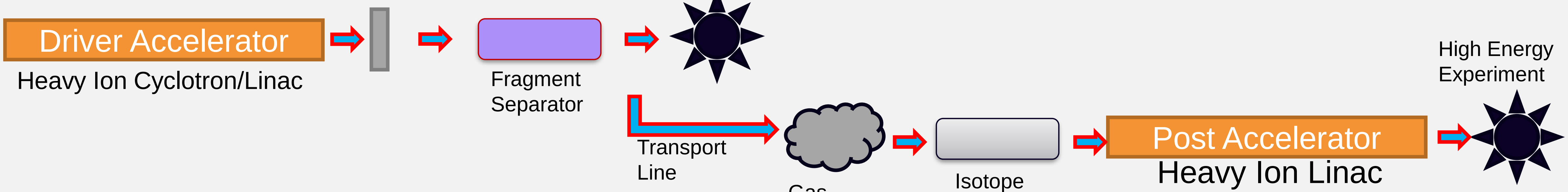
Charge
Breeder

Post Accelerator

Heavy Ion Linac

High Energy
Experiment

In-Flight



Driver Accelerator

Heavy Ion Cyclotron/Linac

Thin
Production
target

Fragment
Separator

High Energy
Experiment

Transport
Line

Gas
Ion-stopper

Isotope
Separator

Post Accelerator

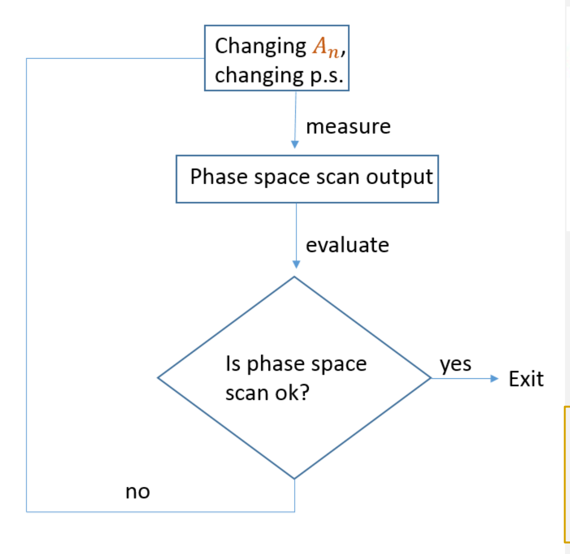
Heavy Ion Linac

High Energy
Experiment

Backup Slides

Multipole tuning for MRMS and HRMS

- Tuning is performed onto $\varepsilon_{rms,n}$ and H_x[1] looking into diagnostics BI.07 at 40 keV for HRMS.
  - Very large variation of emittance $(\sim 10\varepsilon_{rms,n,optimum})$
  - No needed to have specific beam phase space shape as soon as the Allison scanner can measure it.
  - Run time of hours.
  - Modification of A_n coefficients via Down Hill algorithm.
  - The procedure may stack in a relative minimum.
- Image point slits open.
- Tested in simulation with error of the multipole components of 30%-50%.

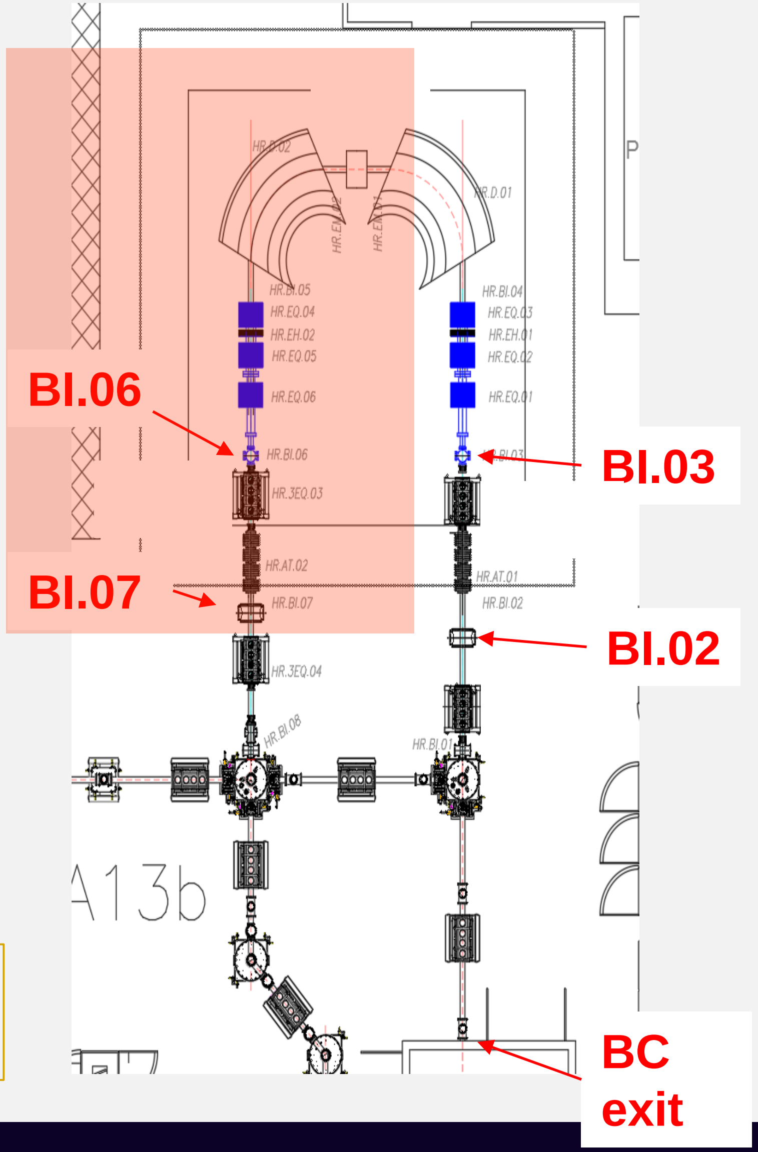


$$\phi(\rho,\theta) = \sum_n A_n \rho^n \cos(n\theta)$$

To be changed by the optimization algorithm

Fixed per each electrode position

Python script or TraceWin VA via EPICS variables



BI.06

BI.07

BI.03

BI.02

BC exit

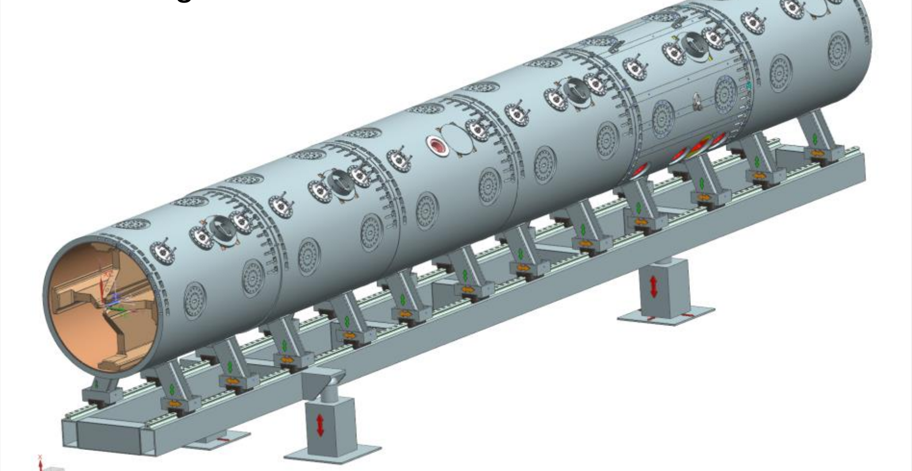
[1] C. K. Allen and T. P. Wangler, Phys. Rev. ST Accel. Beams, vol. 5, p. 124202, 2002.

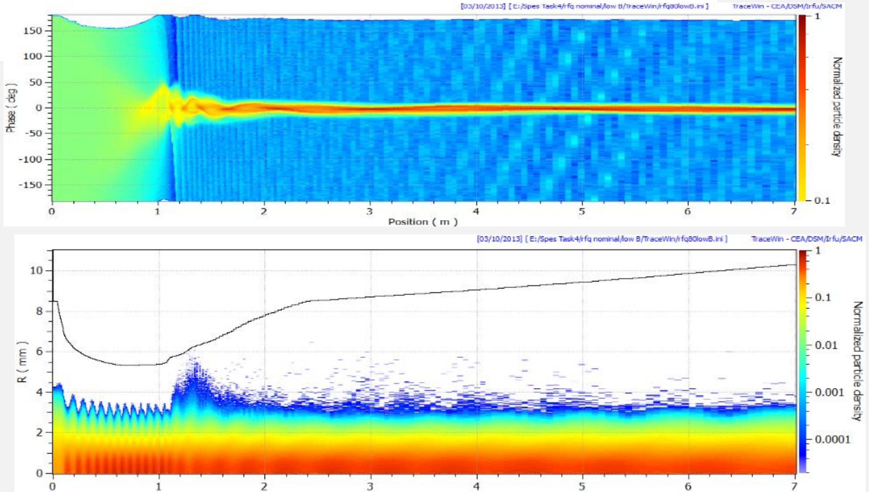
Courtesy of L. Bellan

SPES RFQ: Main parameters

Paramater [units]	Design value
Frequency [MHz]	80
In/out. Energy [keV/u]	5.7-727 (β=0.0035-0.0359)
V_{iv}[kV]	63.76-85.85
Beam current [μA]	100
Vane Length [m]	6.95
R_0[mm]	5.29-7.58
ρ/R_0	0.76
Synchronous phase (deg.)	-90 ÷ -20
Focusing Strength B	4.7 ÷ 4
Shunt impedance [kΩ*m]	419-438 (30% margin)
Stored Energy [J]	2.87
RF Power [kW]	115 (with 30 %margin for 3D details and RF joint, and 20% margin for LLRF regulation)
Q_0 value (SF)	16100 (30% margin)
Max power density [W/cm^2]	0.31 (2D), 13 (3D)
max $\delta V_{iv}/V_{iv}$ [%]	±3
Transmission [%]	94
Output Long RMS Emit [keV deg /u]	4.35

The SPES RFQ is designed in order to accelerate beams in CW with A/q ratios from 3 to 7. The RFQ is composed of 6 modules about 1.2 m long each.



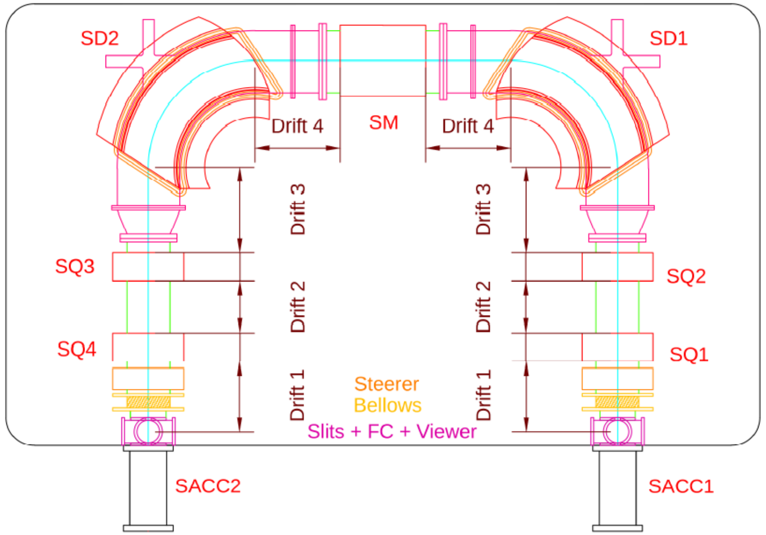


Phase and beam size inside the SPES RFQ

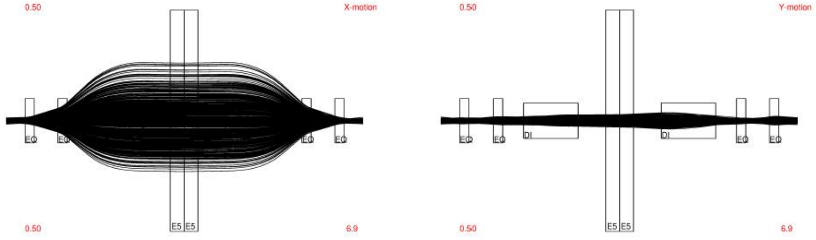
Courtesy of A. Palmieri

The MRMS: nominal separation 1/1000

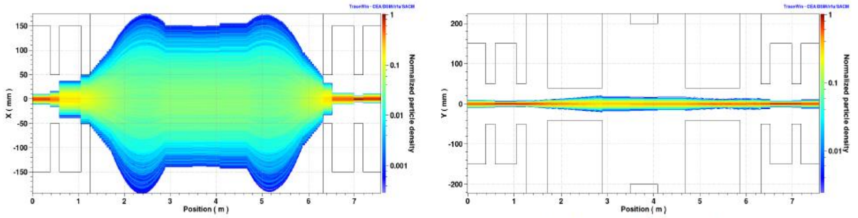
Spectrometer on High Voltage Platform: -120 kV.



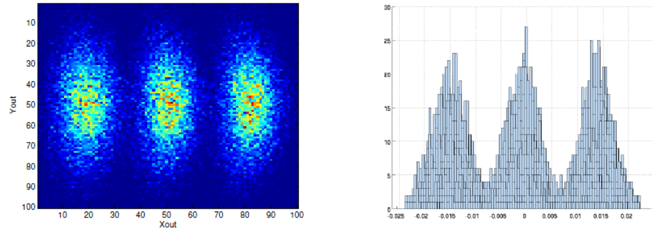
- The optics is composed by 4 electrostatic quadrupoles, 2 dipoles and a 12° order multipole.
- Dipole characteristics: 0.750 m bending radius, 90° bending angle. External edge curvature: 2.6 m. Edge angles β=33.35°. Horizontal aperture 0.4 m. Vertical aperture 0.08 m.
- Both the four quadrupoles are x defocusing.
- BD Benchmarking with COSYINFINITY.
- Required Platform stability of the order of 0.01% in voltage.



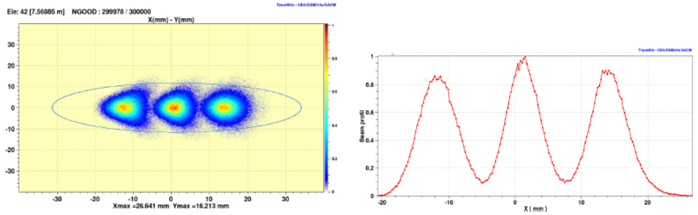
(a) X COSY envelope. (b) Y COSY envelope.



(c) X TraceWin envelope. (d) Y TraceWin envelope.



(a) X-Y COSY distribution. (b) X COSY distribution.



(c) X-Y TraceWin distribution. (d) X TraceWin distribution.

Beam separated on **A/q** of 1/1000